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DEVELOPMENT OF COMPOSITE CONSTRUCTIONS WITH IMPROVED RAIN EROSION RESISTANCE

HUGHES AIRCRAFT COMPANY

PREPARED FOR

NAVAL AIR SYSTEMS COMMAND

JULY 1974

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This report describes the continued investigation of composite constructions with improved rain erosion resistance. The studies included the effect on the rain erosion resistance, as determined by whirling arm tests, of such variables as fiber angle, impact angle, matrix, reinforcement, and reinforcement configuration. Matrices evaluated included a rigid epoxy, a polysulfone and a phenoxy. Reinforcements included Nomex, Kevlar, Dacron and combinations of ECG or SCG glass with Dacron and Nomex, respectively.

20. ABSTRACT (Continued)

Much of the work involved the effect of fiber angle and impact angle on the rain erosion resistance of end-oriented Nomex/epoxy composites. Based on these test results, composite constructions fabricated from several multidimensional Nomex-glass fabrics were evaluated for rain erosion resistance. The test results show that, with respect to rain erosion resistance, the multidimensional constructions are superior to the conventional glass fabric-reinforced laminated composites but inferior to the unidirectionally-reinforced, end-oriented composites.

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FOREWORD

The work described in this report was performed by Hughes Aircraft Company, Equipment Engineering Divisions, Culver City, California under Contract N00019-73-C-0288 under the technical management of Mr. Maxwell Stander, Materials and Processes Branch, Code AIR-52032D, Naval Air Systems Command, Washington, D.C. 20360 and by Materials Sciences Corporation, Blue Bell, Pennsylvania under subcontract to Hughes Aircraft Company.

This report covers work from 1 February 1973 to 31 May 1974. Previous work on this program was performed under Contracts N00019-70-C-0315, N00019-71-C-0167 and N00019-72-C-0257 covering the period from 1 April 1970 to 31 December 1972.

The assistance to Mr. A. A. Castillo in preparing the composite moldings is gratefully acknowledged.

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ABSTRACT

This report describes the continued investigation of composite constructions with improved rain erosion resistance. The studies included the effect on the rain erosion resistance, as determined by whirling arm tests, of such variables as fiber angle, impact angle, matrix, reinforcement, and reinforcement configuration. Matrices evaluated included a rigid epoxy, a polysulfone and a phenoxy. Reinforcements included Nomex, Kevlar, Dacron and combinations of ECG or SCG glass with Dacron and Nomex, respectively. Much of the work involved the effect of fiber angle and impact angle on the rain erosion resistance of end-oriented Nomex/epoxy composites. Based on these test results, composite constructions fabricated from several multidimensional Nomex-glass fabrics were evaluated for rain erosion resistance. The test results show that, with respect to rain erosion resistance, the multidimensional constructions are superior to the conventional glass fabric-reinforced laminated composites but inferior to the unidirectionally-reinforced, end-oriented composites.

SUMMARY

This technical report covers the fourth year's effort in the development of fiber-reinforced composites with improved resistance to rain erosion at near-sonic speeds. The development of improved composite constructions and their successful application in aircraft radome structures will allow substantial cost savings through less frequent repair and replacement.

The program consisted of the determination of the relative rain erosion resistance of a large number of fiber-reinforced plastics composites by whirling arm tests conducted at Dornier System GmbH, West Germany. The variables evaluated included fiber angle, impact angle, matrix, reinforcement and reinforcement configuration. The following types of specimens were evaluated:

- A unidirectionally-reinforced, end-oriented Nomex/epoxy at various fiber angles and impact angles.
- Various multidimensional constructions combined with a standard epoxy matrix.
- Various matrices including a rigid epoxy, polysulfone and phenoxy reinforced with either glass fabric or graphite fibers.

In addition, the dielectric constant and loss tangent at X-band were calculated from electrical measurements made on two typical multidimensionally-reinforced composites.

The results of the rain erosion tests showed that the rain erosion resistance of the multidimensional constructions, though superior to that of the conventional glass fabric-reinforced laminated composites, is inferior to that of the unidirectionally-reinforced, end-oriented composites. The Nomex/glass composites were found to be far superior, with respect to rain erosion resistance, to the Kevlar composites evaluated.

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INTRODUCTION

Previous studies of reinforced plastic composite constructions with improved rain erosion resistance (Contracts N00019-70-C-0315, N00019-71-C-0167 and N00019-72-C-0257) allow the following conclusions to be drawn regarding rain erosion resistance:

- unidirectional, fiber-reinforced, end-oriented composites are far superior to other constructions
- polymeric fibers such as Nomex (a polyaromatic nylon) and Dacron (polyethylene terephtahalate) are superior to glass fibers (composites containing polymeric fibers are not subject to spallation as are composites containing glass fibers)
- high fiber loadings are essential in glass composites
- high fiber loadings are superior to low fiber loadings in polymeric fiber composites, though lower fiber loadings are acceptable
- flexibilized matrices are somewhat superior to rigid matrices when reinforced with glass fibers, although polymeric fibers such as Nomex give good erosion resistance with a variety of epoxy matrices from rigid to flexibilized
- erosion resistance is dependent on fiber angle (where fiber angle impact angle) for glass composites
- a 4-D Omniweave construction woven from Nomex was found to have moderately good erosion resistance and to be far more rain erosion resistant than a similar Omniweave material woven from S glass

The foregoing test results coupled with the requirement for relatively thin-walled radome structures for most military aircraft antennas dictated that much of the future activities be concentrated on multidimensional constructions. Such constructions will likely be woven from polymeric fibers and will contain a high volume fraction of tightly packed fibers.

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Constructions will be considered which contain polymeric fibers at and near the outer surface for rain erosion resistance and some type of structural reinforcing fibers (probably glass) in the sub-structure to impart structural strength.

Composite constructions will be considered for two types of radome structure:

1. Relatively thin-walled, with broadband capability
2. Thick-walled, with thickness and dielectric properties adjusted to operate efficiently over a specified narrow frequency range.

Emphasis will be placed on the development and evaluation of relatively thin composite constructions meeting the broadband requirement, since a thicker version of such constructions would be expected to meet the requirements for rain erosion resistance and structural strength.

Specific constructions will be based on the results of analytical studies. Rain erosion test results accumulated thus far will serve as a basis for these studies involving the choice of a suitable compromise between rain erosion resistance and in-plane structural properties.

Plastic composites based on these constructions will be fabricated and evaluated for both rain erosion resistance and structural properties. These test results will be used as required in continued analytical studies to develop composite constructions embodying the optimum combination of rain erosion resistance and structural strength.

EXPERIMENTAL

RAIN EROSION TESTING

All of the rain erosion tests were run in the whirling arm facility operated by Dornier System GmbH, Friedrichshafen, West Germany.

Dornier's apparatus consists essentially of a rotor driven by a powerful electric motor. The rotor is contained inside a chamber which may be partially evacuated as required for high testing speeds. Water drops of the required size and quantity are injected into the chamber at eight points around the periphery. The specimen holder can be adjusted to allow impact angles ranging from 15 to 90 degrees.

The specimens consist of circular discs 16.75 mm (0.660 inch) in diameter by 5.08 mm (0.200 inch) maximum thickness. The specimen is secured to a specimen holder at the end of the rotor by means of a retaining ring. During the test, one face of the specimen is subjected to simulated rain erosion under controlled test conditions. All of the specimens evaluated during this reporting period were tested under the following conditions:

- Velocity – 333 meters/second
- Droplet diameter – 1.2 mm
- Impact angle – 30 to 90 degrees
- Exposure time – 15 to 120 seconds
- Rain density – 1.2×10^{-5} (equivalent to a rainfall rate of 7.5 inches per hour)

Prior to testing, the weight and thickness of each specimen were measured and recorded. The responses measured for a given exposure time were weight loss and erosion depth. In addition, the specimens were examined

visually, with specimens of particular interest also being photographed. Repeated weight loss measurements of the same specimen were not made for various exposure times. Instead, one or more sets of specimens machined from the same composite were subjected to different exposure times.

SPECIMEN PREPARATION

Impregnation of Reinforcements

The multidimensional fabrics (except for the Dacron/glass fabric) were impregnated with an epoxy resin system consisting of 100 PBW Epon 828 and 22 PBW of menthane diamine. Prior to impregnation, the resin system was degassed under vacuum at room temperature and the fabric was oven-dried at 225°F for one hour. The fabric was placed in the impregnation apparatus and a vacuum applied. While maintaining the vacuum, the fabric was covered with the resin mixture. After all bubbling stopped, the vacuum was released.

The Dacron/glass fabric was impregnated with a mixture of 100 PBW of Epon 828 and 14.3 PBW MPDA by the same general procedure.

The roving or yarn used in preparing the unidirectionally-reinforced, end-oriented specimens was impregnated with the resin system, Epon 828/MPDA, after winding on a series of frames. A specified number of turns of the roving was wound on each of several frames as shown in Figure 1. During winding, the portions of the fibers nearest the frame spools were coated with a catalyzed polyurethane elastomer, leaving a 4-inch long uncoated center section. After curing the polyurethane, the fiber loops were removed from the frames and vacuum-pressure impregnated with the resin system. In practice, the fiber loops were bent into a U-shape and placed, with the uncoated portion of the fibers downward, in a small beaker. The vacuum-pressure impregnation consisted of covering the fiber loops with the resin while under vacuum and then increasing the pressure to 90-100 psig.

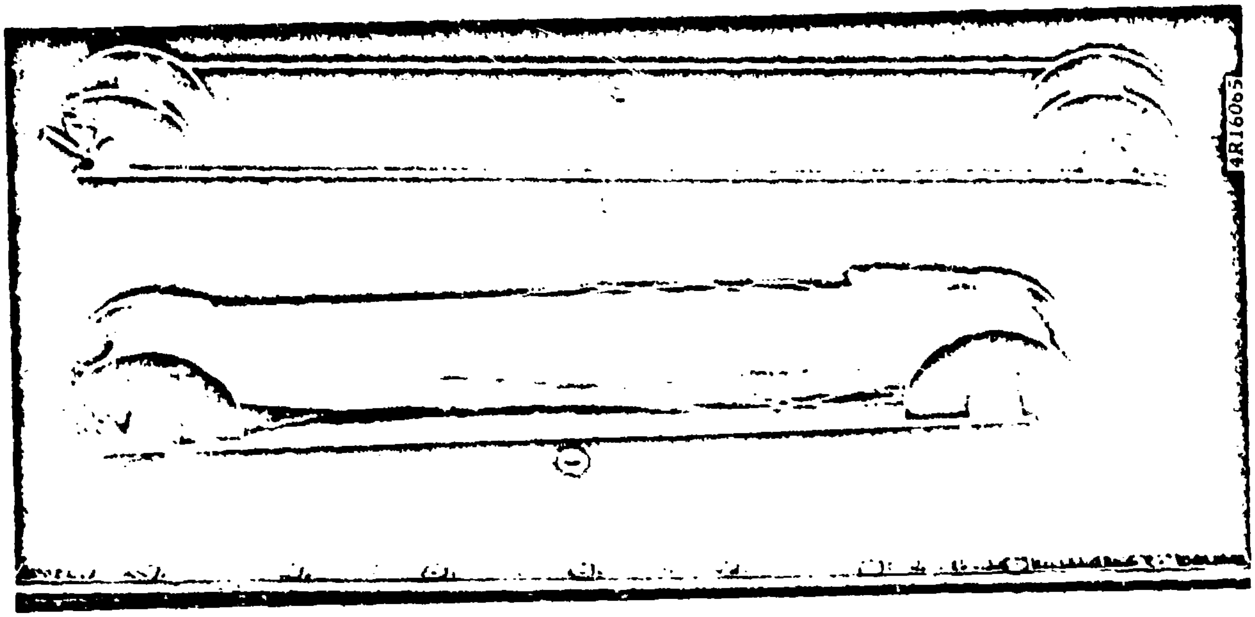

Figure 1. Roving wound on frame.

Plasma Etching

The effect of plasma-etching Nomex fibers on the rain erosion resistance of a Nomex/epoxy composite was investigated. It was felt that plasma etching would result in improved adhesion between the fibers and the epoxy matrix. The apparatus consists essentially of a small glass chamber through which is flowing continuously a low pressure gas which is subjected to radio frequency electromagnetic radiation by electrodes located outside the vacuum chamber. The resulting plasma reacts with the surface layers of the material being treated, usually resulting in improved bondability of typical organic polymers. The Nomex fibers were etched for 10 minutes with an air plasma at a pressure of 2 torr. The Nomex was etched immediately after winding and shortly before impregnation with the epoxy resin.

Molding Procedure

The impregnated fabric, covered with excess resin, was placed between two 1/8-inch thick aluminum plates. This assembly was placed in a laboratory press and cured at a pressure of 50 psi. The cure conditions were one hour at 250°F and 3 hours at 350°F for the 828/menthane diamine

system and one hour at 225°F and one hour at 325°F (plus 16 hours postcure at 325°F) for the Epon 828/MPDA system.

The loops of impregnated fibers are secured by wire hooks in a frame assembly as shown in Figure 2. Tension is applied by a spring on the stem of the eye loop on the outside of the frame. The tension is adjusted by the nut on the stem to approximately 40 pounds.

After the impregnated roving is centered in the mold cavity, the frame is unclamped from the press. The punch is positioned in the cavity and the press closed to apply pressure to the layup as shown in Figure 3. Usually, shims are placed between the cavity and the punch to allow the molding of a composite of closely controlled thickness and composition.

A typical molded composite bar is shown immediately after being removed from the mold (Figure 4). The center molded portion is nominally 3 inches long with a cross section approximately three-quarters of an inch square.

Machining of Specimens

The excess material is cut away from the molded composite leaving an oblong bar approximately 3 inches long. After cutting a quarter-inch section from each end and discarding, the remaining material is chucked. in a lathe and ground to a diameter of 0.660 inch. Individual specimens are cut off with a diamond saw mounted in a tool post grinder. Finally, one surface of each specimen is surface ground to obtain the final thickness of 0.200 inch. Profilometer inspection has shown the surface roughness to vary from 11 to 14 microinches.

Specimens are machined from composites prepared from multidimensional fabrics with the specimen face parallel to the original surface of the tape. The surface of these specimens is left undisturbed.

Prior to submission for rain erosion testing, the thickness and weight of each specimen are measured and recorded.

Specimens for dielectric measurements of the multidimensional composites were made by bonding together four layers of the cured composite to give a block approximately 0.400 inch thick and machining this block to fit an X-band waveguide, nominally 0400 inch by 0.900 inch.

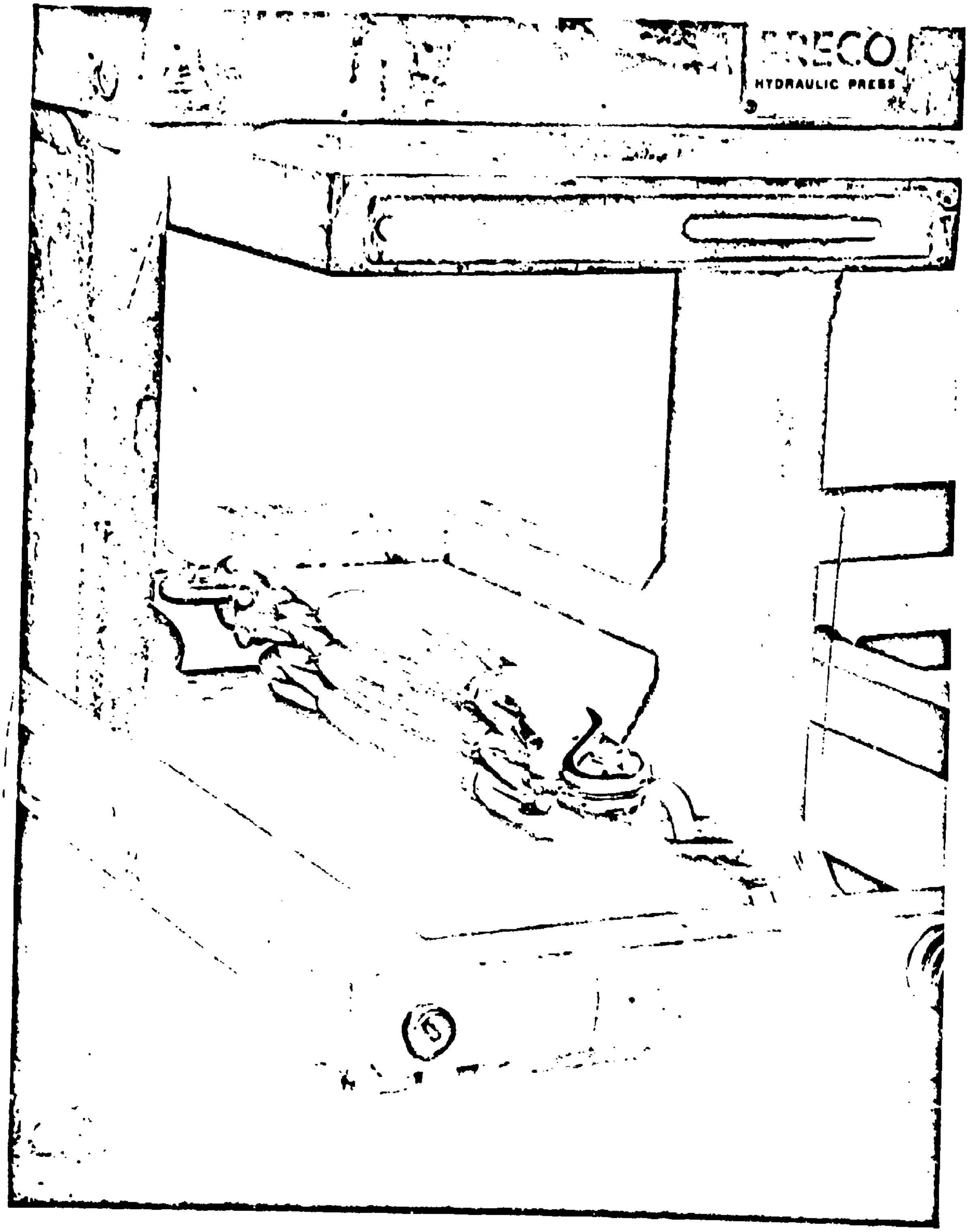

Figure 2. Frame assembly with impregnated roving in place.

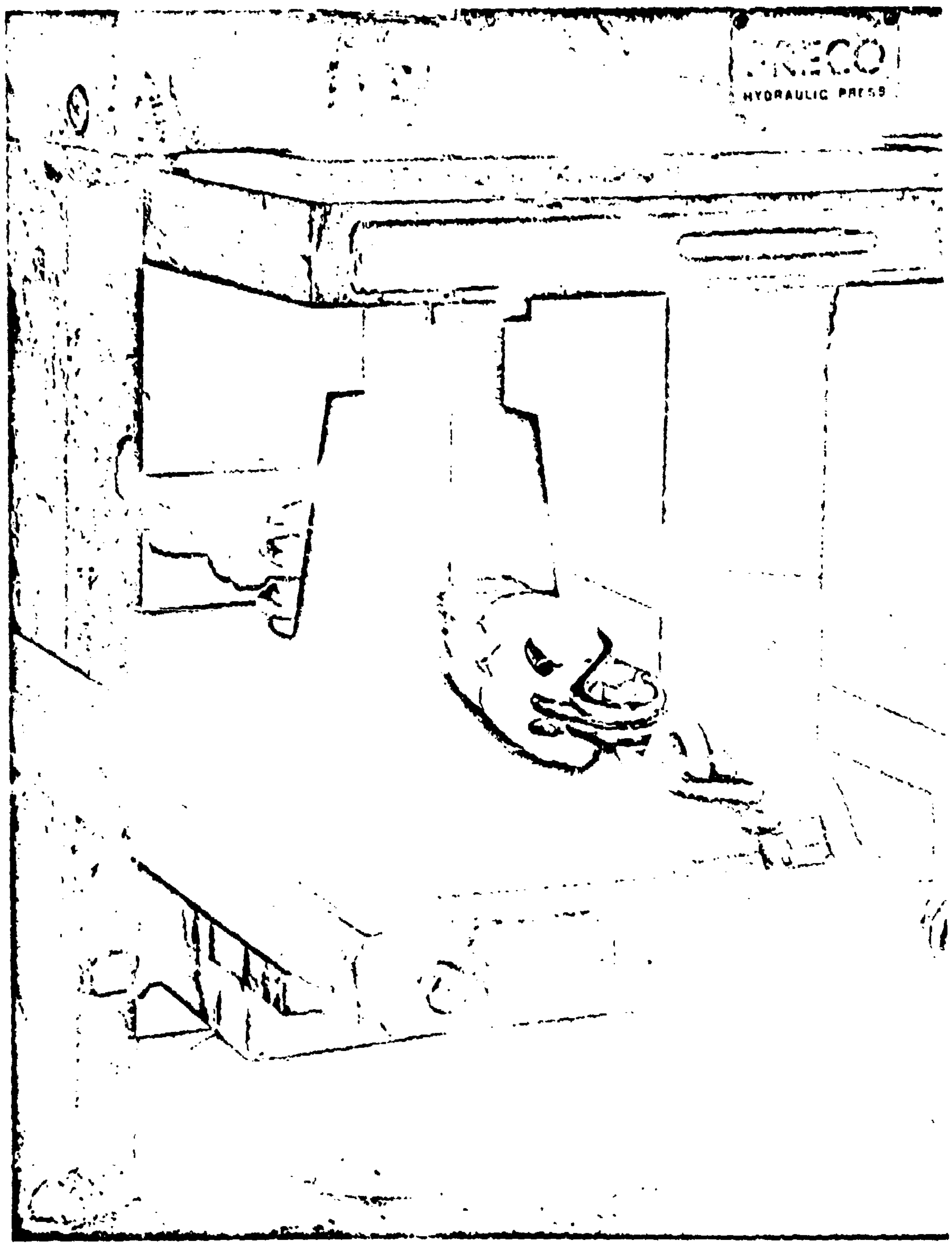

Figure 3. Molding of unidirectional composite.

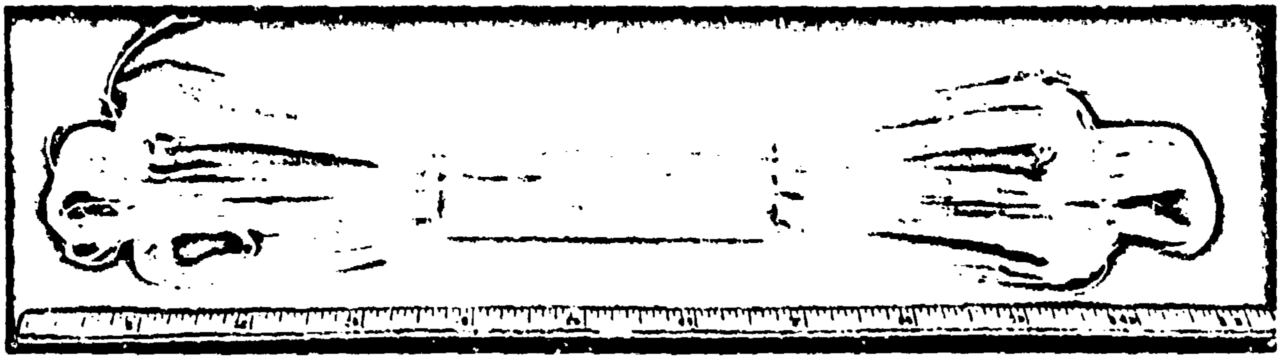

Figure 4. Composite bar cured in channel mold.

Determination of Composition

The composition of each molded, unidirectional composite is controlled closely to the desired value by molding to a fixed volume impregnated roving or yarn with a known weight per unit length for the unimpregnated reinforcement.

ANALYTICAL STUDIES

Analytical studies leading to the choice of optimum composite constructions were performed by Materials Sciences Corporation, Blue Bell, Pennsylvania. The MSC investigation, under the supervision of Dr. B. Walter Rosen, consisted of the following specific tasks:

1. The available rain erosion data from tests conducted for Hughes by Dornier were organized and classified to allow the determination of the relative effects of the various material parameters.
2. A test program was defined to assess the effects of parameters for which data was not previously available.
3. Composite constructions were defined which would combine good resistance to rain erosion and sufficient in-plane structural properties to function as a structural material for radome applications.

The final report by MSC covering this investigation is attached as an Appendix.

RAIN EROSION TEST RESULTS

The results of the rain erosion tests performed by Dornier are summarized in Tables 1 through 8. The figure references in the table titles or in the tables refer to photographs of exposed test specimens. The test results are discussed briefly in the following sections.

Effect of Fiber Angle for 90° Impact Angle

Four specimens were machined from each of four similar Nomex/epoxy composite bars with a nominal fiber content of 50 volume-percent. The specimens were machined from each composite bar with fiber angles with respect to the specimen surface of 90, 60, 45 and 30 degrees, respectively. The specimens were tested under standard conditions for times of 30, 60, 90 and 120 seconds. Table 1 tabulates the weight loss for the various fiber angles and test times while Table 2 tabulates the corresponding change in specimen thickness.

It is evident from Table 1 that rain erosion resistance increases markedly with increasing fiber angle. The thickness change data in Table 2, though not too informative, show the 90° specimens to change in thickness only slightly compared with the other specimens for an exposure time of 120 seconds.

TABLE 1. EFFECT OF FIBER ANGLE (90° IMPACT ANGLE) ON WEIGHT LOSS OF END-ORIENTED NOMEX/EPOXY (FIGURE 5)

Exposure Time, Seconds	Weight Loss, Milligrams			
	Fiber Angle, Degrees			
	30	45	60	90
30	212	64	32	23
60	81	112	46	31
90	153	101	62	30
120	208	122	74	38

TABLE 2. EFFECT OF FIBER ANGLE (90° IMPACT ANGLE) ON SPECIMEN THICKNESS OF END-ORIENTED NOMEX/EPOXY

Exposure Time, Seconds	Decrease in Thickness, Mils*			
	Fiber Angle, Degrees			
	30	45	60	90
30	-3.2	-4.7	-2.7	-0.1
60	-3.2	-3.2	-1.3	1.0
90	2.0	2.0	0.4	-0.1
120	8.8	8.0	4.8	-0.1

*A negative value indicates a measured increase in thickness due to surface roughness.

Effect of Impact Angle for 90° Fiber Angle

Eight specimens were machined from each of two similar Nomex/epoxy composite bars with a nominal fiber content of 50 volume-percent. All of the specimens were machined with the fibers perpendicular to the specimen face. The specimens were tested under standard conditions for times of 30 and 60 seconds. The weight loss data is tabulated in Table 3, while Figure 6 shows the effect of the exposure to the test conditions on specimens machined from one of the two composites.

As expected, the amount of weight loss is seen to increase with increasing impact angle. The specimen thickness changed very little for all of the specimens and these changes, therefore, are not tabulated.

Effect of Fiber Angle and Impact Angle

Four specimens were machined from each of four similar Nomex/epoxy composite bars with a nominal fiber content of 50 volume-percent. The four specimens were machined from each composite bar with fiber angles with respect to the specimen surface of 90, 60, 45 and 30 degrees, respectively. The specimens were tested under standard conditions for times of 30, 60, 90 and 120 seconds at impact angles of 90, 60, 45 and

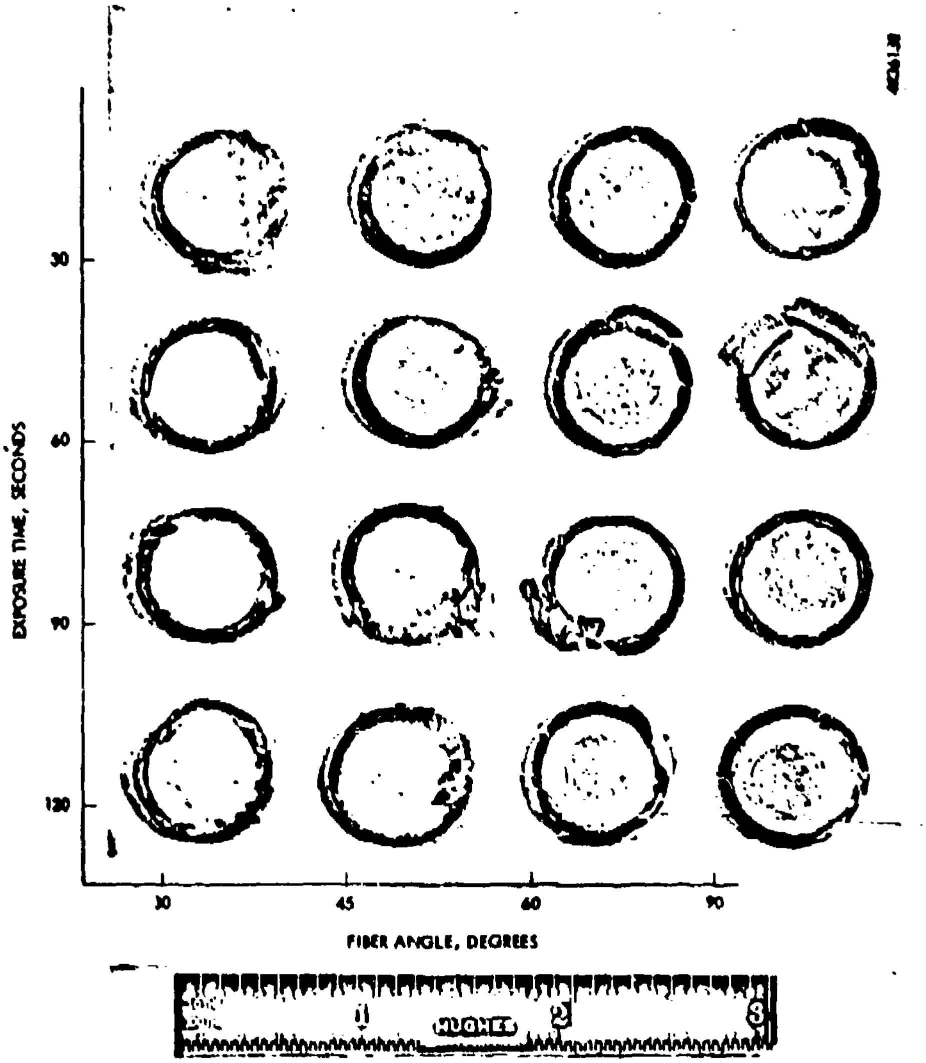

Figure 5. Effect of fiber angle on rain erosion resistance of end-oriented Nomex/epoxy.

TABLE 3. EFFECT OF IMPACT ANGLE (90° FIBER ANGLE) ON WEIGHT LOSS OF END-ORIENTED NOMEX/EPOXY (FIGURE 6)

Impact Angle, Degrees	Weight Loss, Milligrams			
	Exposure Time, Seconds			
	30		60	
	Composite N-25	Composite N-26	Composite N-25	Composite N-26
30	3	5	5	6
45	5	4	8	6
60	12	11	12	12
90	15	11	27	20

30 degrees, respectively. Each specimen was aligned in the specimen holder at the specified angle so that the rain drop velocity vector was parallel to the fiber direction. The fiber direction with respect to the specimen surface for these specimens corresponded, in all cases, to the required impact angle. The effect of the exposure on weight loss of the specimens is summarized in Table 4.

The results, despite some apparently anomalous data, indicate that greater weight losses are to be expected for the lower fiber/impact angles. Most of the specimens were apparently slightly thicker after rain erosion testing due to surface irregularities and protruding fibers and the thickness data are therefore, not included.

Effect of Plasma Treatment of Nomex Fibers

Eight specimens were machined from each of four Nomex/epoxy composite bars with a nominal fiber content of 50 volume-percent, with one composite having been prepared from Nomex yarn which had been etched in an air plasma. The specimens, all of which were 90 degree end-oriented, were tested under standard conditions at an impact angle of 90°

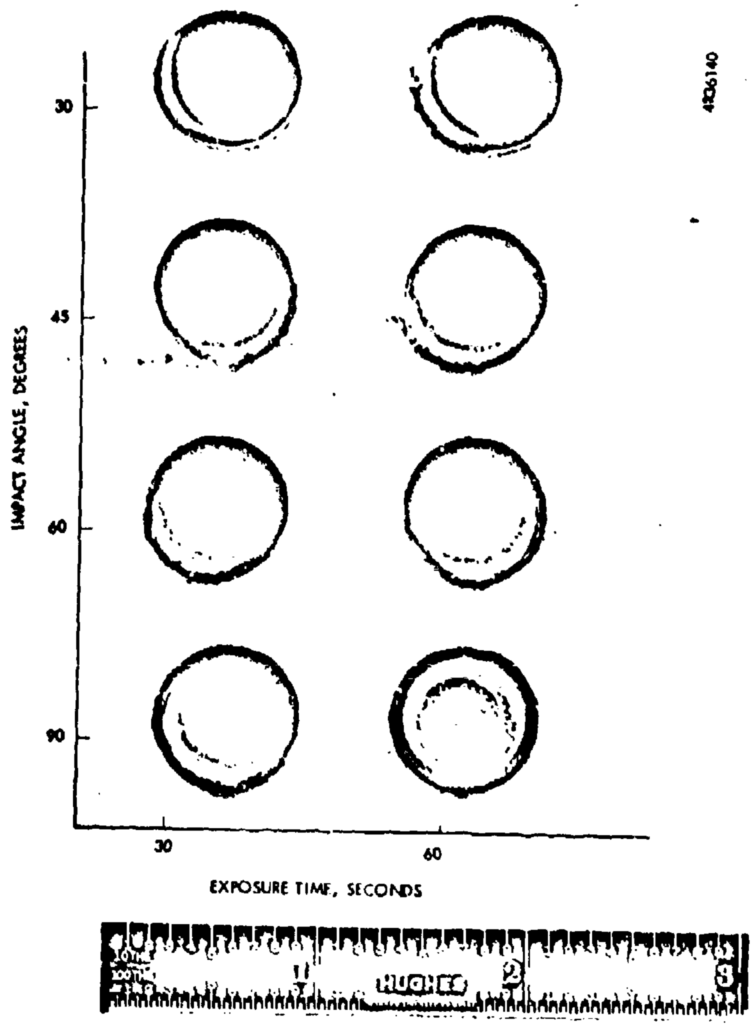

Figure 6. Effect of impact angle on rain erosion resistance of end-oriented Nomex/epoxy (composite N-25)

TABLE 4. EFFECT OF FIBER ANGLE AND IMPACT ANGLE ON WEIGHT LOSS OF END-ORIENTED NOMEX/EPOXY (FIGURE 7)

Exposure Time, Seconds	Weight Loss, Milligrams			
	Fiber Angle/Impact Angle, Degrees			
	30	45	60	90
30	60	36	38	29
60	58	42	36	31
90	86	68	43	73
120	96	104	72	66

for times of 30, 60, 90 and 120 seconds. In Table 5, the weight loss values for the specimens from the four composites are compared.

From an examination of the above data and the exposed specimens (Figures 8 and 9), it is apparent that a small but significant increase in rain erosion resistance is realized by plasma etching of the Nomex.

TABLE 5. EFFECT OF PLASMA TREATMENT OF NOMEX FIBERS ON WEIGHT LOSS OF NOMEX/EPOXY

Exposure Time, Seconds	Weight Loss, Milligrams			
		Non-Plasma-Treated Nomex		
	Plasma-Treated Nomex	Composite N-28	Composite N-29	Composite N-30
30	8	12	18	21
	13	11	19	17
60	18	18	30	29
	15	22	32	33
90	30	30	39	32
	23	29	47	39
120	36	39	45	60
	33	40	56	70

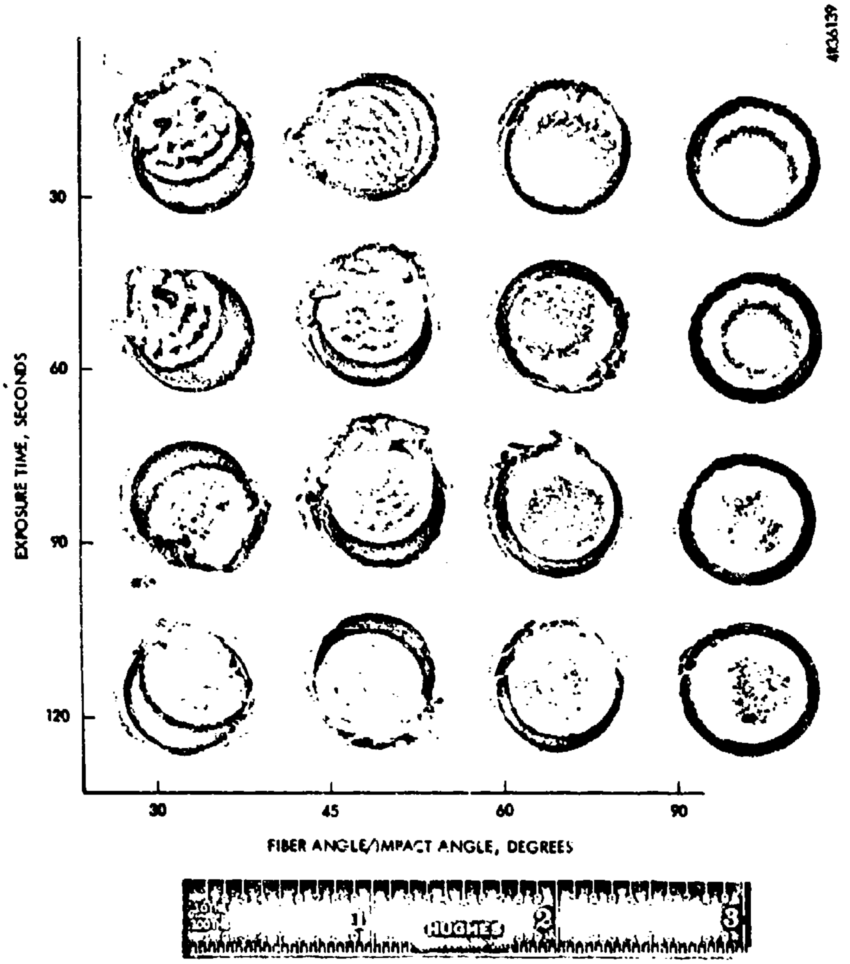

Figure 7. Effect of fiber angle and impact angle on rain erosion resistance of end-oriented Nomex/epoxy

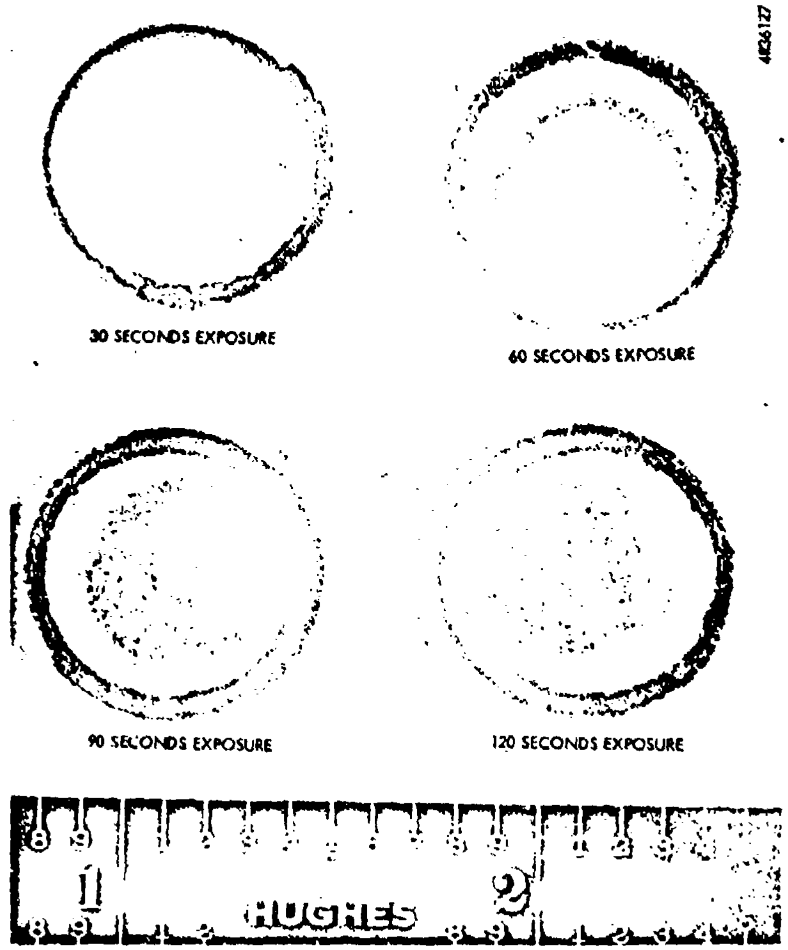

Figure 8. End-oriented Nomex/epoxy fabricated from plasma-etched Nomex yarn.

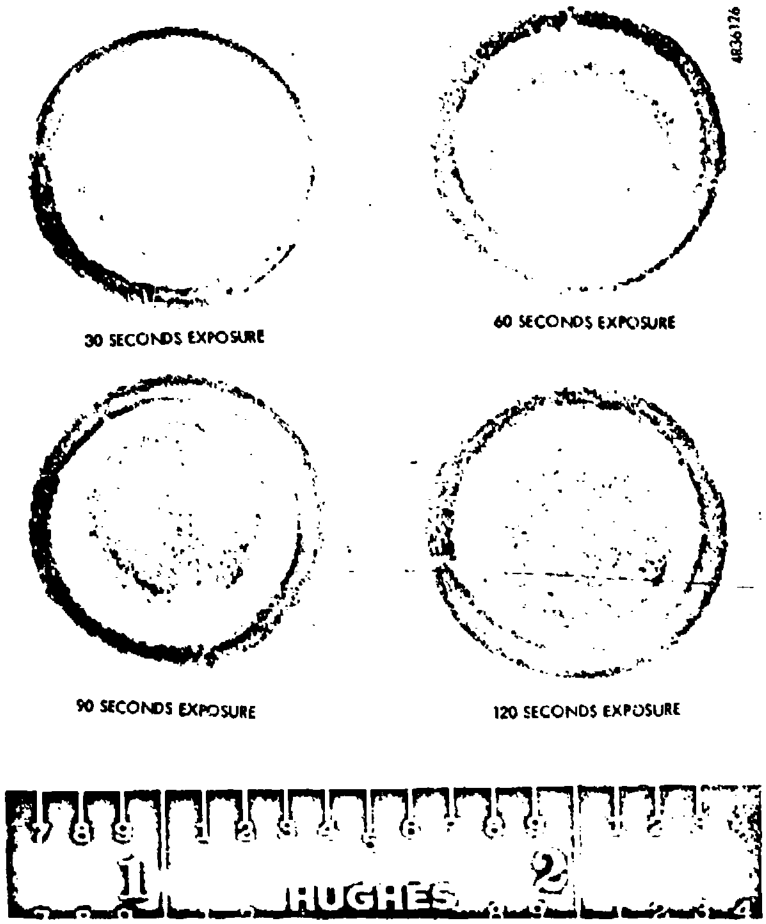

Figure 9. End-oriented Nomex/epoxy fabricated from unetched Nomex yarn.

Multidimensional Composites

A total of six multidimensional fabric constructions were evaluated in the form of epoxy composites as follows:

3D-12: Angle-interlock, through-the-thickness interlock, Dacron/glass (see Figure 10) (Woven Structures, Inc.).

3D-13: Orthogonal construction consisting of 15 volume-percent glass fibers (based on total volume-percent fibers) in the X and Y directions and 70 volume-percent Nomex fibers in the Z direction. (Fiber Materials, Inc.).

3D-14: Angle-interlock, layer-to-layer interlock, Nomex/glass (see Figure 11) (Fabric Development, Inc.).

3D-15: Angle-interlock, through-the-thickness, high angle interlock, Nomex/glass (see Figure 12) (Fabric Development, Inc.).

3D-16: Angle-interlock, through-the-thickness, 45° interlock, Nomex/glass (see Figure 13) (Fabric Development, Inc.).

3D-17: Angle-interlock, layer-to-layer interlock, Kevlar 29 (Fabric Development, Inc.).

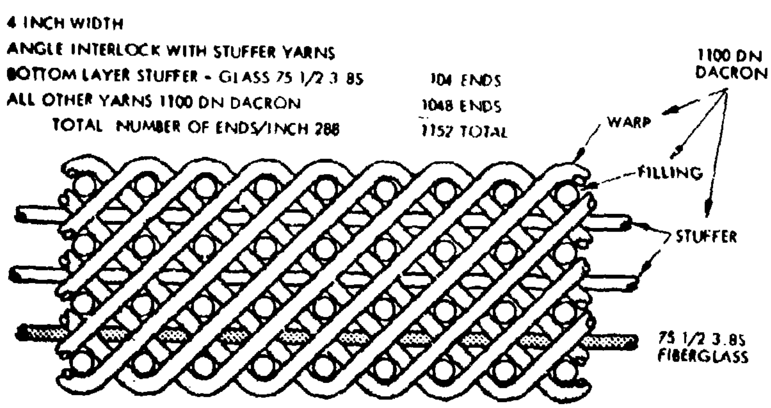

Figure 10. Construction details dacron/glass angle-interlock fabric 3D-12.

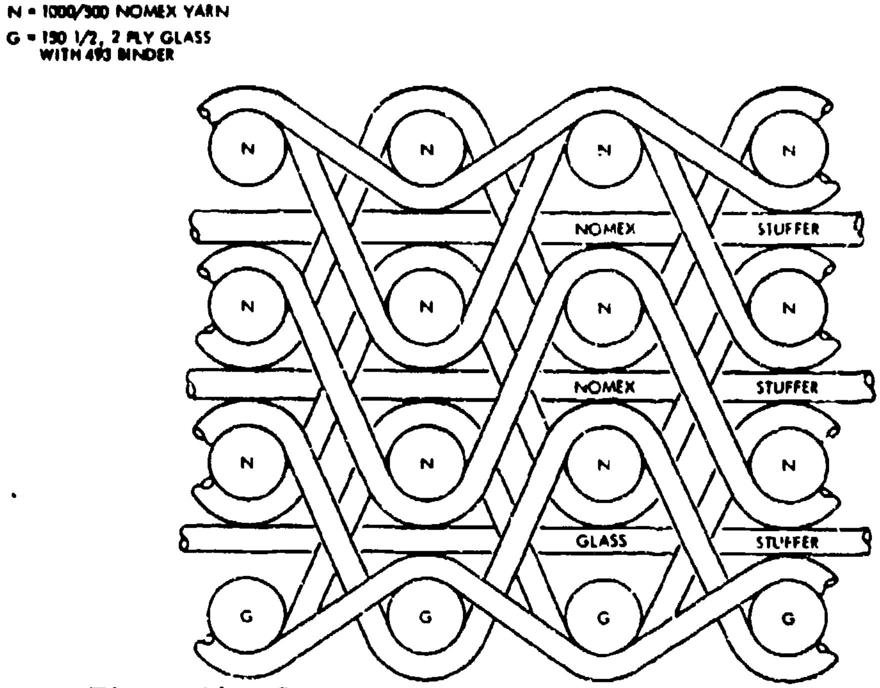

Figure 11. Construction details Nomex/glass layer-to-layer angle-interlock fabric 3D-14.

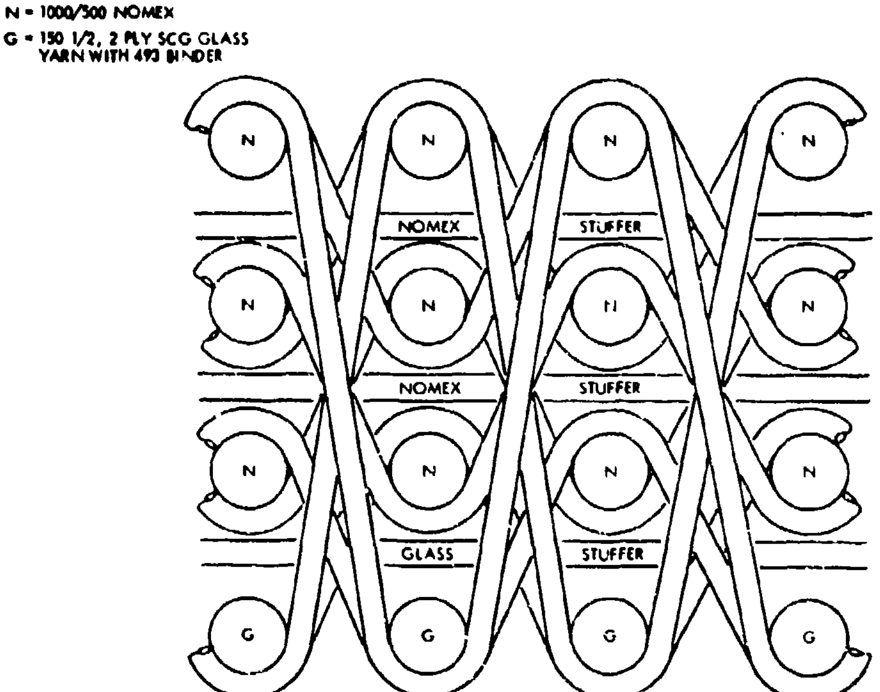

Figure 12. Construction details - Nomex/glass, through-the-thickness, high angle, angle-interlock fabric 3D-15.

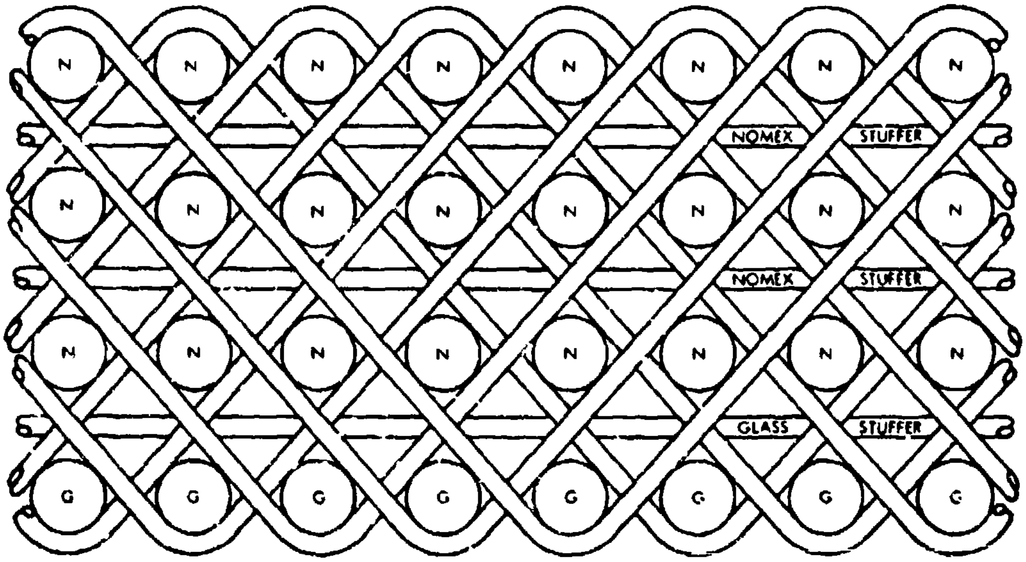

Figure 13. Construction details - Nomex/glass, through-the-thickness, 45° angle-interlock fabric 3D-16.

The Dacron/glass angle-interlock fabric was the first fabric woven with the goal of combining good rain erosion resistance and adequate structural properties. The next four Nomex/glass fabrics were chosen for evaluation based on recommendations made by Materials Sciences Corporation. The Kevlar 29 fabric was evaluated since it was available at no cost and was of interest due to the unusual structural properties of Kevlar fibers.

A total of nine tests was run on each composite made from these fabrics, three each at respective exposure times of 15, 30 and 60 seconds at an impact angle of 90 degrees under standard conditions. Table 6, which summarizes the data, indicates that all of the fabrics (with the exception of the Kevlar 29), while superior to glass fabric laminated epoxies or multidimensional composites containing all glass are inferior in rain erosion resistance to end-oriented composites containing either Nomex or Dacron fibers. For the sake of comparison, previous rain erosion data on a conventional 181 E glass-epoxy laminate and an end-oriented glass-epoxy also are included. Surprisingly, the high-angle angle-interlock Nomex/glass was

TABLE 6. RELATIVE RAIN EROSION RESISTANCE OF EPOXY COMPOSITES FABRICATED FROM VARIOUS MULTIDIMENSIONAL FABRICS

Specimen Code	Material Description	Exposure Time, Seconds	Weight Loss, Mg	Erosion Depth, Mils	Appearance	Figure Refs.
3D-12A	Dacron/glass, through-the-thickness interlock with Epon 828/MPDA, resin content 40.5 weight-percent	15	45	2.0	Moderately eroded with few surface fibers protruding	
3D-12B		15	47	1.7		
3D-12C		15	79	5.8		14
3D-12D		30	65	3.4	Moderately eroded with few surface fibers protruding	
3D-12E		30	88	6.8		
3D-12F		30	83	6.0		14
3D-12G		60	94	3.3	Very eroded with many surface fibers protruding	
3D-12H		60	91	6.8		
3D-12I		60	106	6.4		14
3D-11A	Nomex/glass, orthogonal construction consisting of 15 volume-percent glass fibers (based on total volume of fibers) in X and Y directions and 70 volume-percent Nomex fibers in Z direction with Epon 828/Menthane Diamine; resin content ~36.8 weight-percent	15	69	4.1	Moderately eroded	
3D-11B		15	50	3.6		
3D-11C		15	77	5.0		15
3D-11D		30	112	10.1		15
3D-11E		30	97	5.1	Moderately eroded	
3D-11F		30	106	5.4		
3D-11G		60	110	11.2		
3D-11H		60	167	15.8	Moderately eroded	
3D-11I		60	118	9.7		15
3D-14A	Nomex/glass, layer-to-layer angle-interlock with Epon 828/Menthane Diamine, resin content = 43.7 weight-percent	15	72	4.5	Extremely eroded	
3D-14B		15	64	7.6		16
3D-14C		15	101	7.3		
3D-14D		30	155	19.8	Extremely eroded	16
3D-14E		30	138	17.8		
3D-14F		30	156	19.4		
3D-14G		60	167	21.1	Extremely eroded	16
[illegible]		60	192	25.5		
[illegible]		60	169	24.0		
3D-15A	Nomex/glass, through-the-thickness, high angle, angle-interlock with Epon 828/Menthane Diamine, resin content = 50.2 weight-percent	15	162	22.8	Extremely eroded	17
3D-15B		15	186	17.9		
3D-15C		15	112	12.6		
3D-15D		30	174	20.5	Extremely eroded	17
3D-15E		30	167	18.0		
3D-15F		30	257	39.1		
3D-15G		60	220	29.2	Extremely eroded	17
3D-15H		60	166	16.9		
3D-15I		60	152	9.2		
3D-16A	Nomex/glass, through-the-thickness, 45° angle-interlock with Epon 828/Menthane Diamine, resin content = 41.5 weight-percent	15	69	3.7	Extremely eroded	18
3D-16B		15	82	4.6		
3D-16C		15	73	4.6		
3D-16D		30	84	12.3	Extremely eroded	18
3D-16E		30	104	9.5		
3D-16F		30	120	9.4		
3D-16G		60	127	11.1	Extremely eroded	18
3D-16H		60	133	10.4		
3D-16I		60	121	10.2		
3D-17A	Kevlar 29, layer-to-layer angle interlock with Epon 828/Menthane Diamine, resin content = 56.8 weight-percent	15	182	34.7	Extremely eroded	19
3D-17B		15	186	19.4		
3D-17C		15	163	25.1		
3D-17D		30	141	48.6	Extremely eroded	19
3D-17E		30	128	57.9		
3D-17F		30	112	52.9		
3D-17G		60	530	-	Eroded through	19
3D-17H		60	503	-		
3D-17I		60	512	-		
E-1A[1]	E glass fabric style 181, not end-oriented, Epon 828/MPDA, resin content 33 weight-percent	30	628	69	Deeply eroded	
E-1B[1]		30	615	66	Deeply eroded	
E-1C[2]		30	406	42	Deeply eroded	
E-1D[2]		30	415	41	Deeply eroded	
UD-7A	ECG glass roving, 801 sizing, Epon 828/MPDA, resin content 14 weight-percent	30	13	0	Lightly eroded	
UD-7B		30	15	0	Lightly eroded	
UD-7C		30	13	0	Lightly eroded	
UD-7D		30	14	0	Lightly eroded	

1. Machined surface.
2. Molded surface.

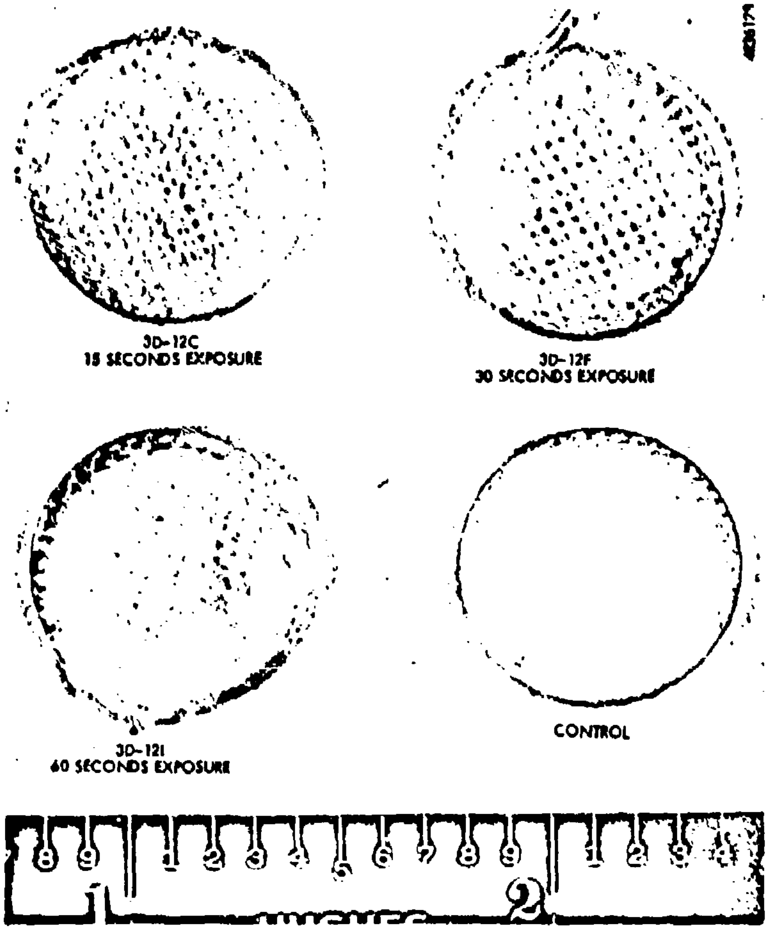

Figure 14. Dacron/glass angle-interlock - Epon 828/ MPDA resin content = 40.5 weight-percent.

3D-12

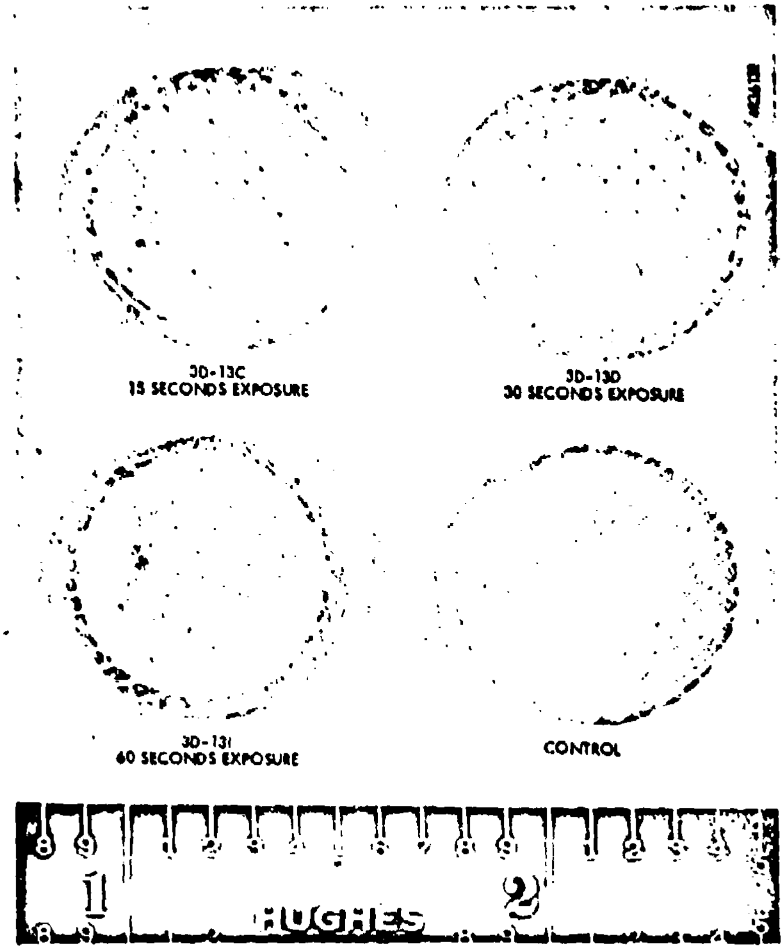

Figure 15. Nomex/glass orthogonal 3-D fabric - Epon 828/menthane diamine; resin content = 26.8 weight-percent.

3 D-13

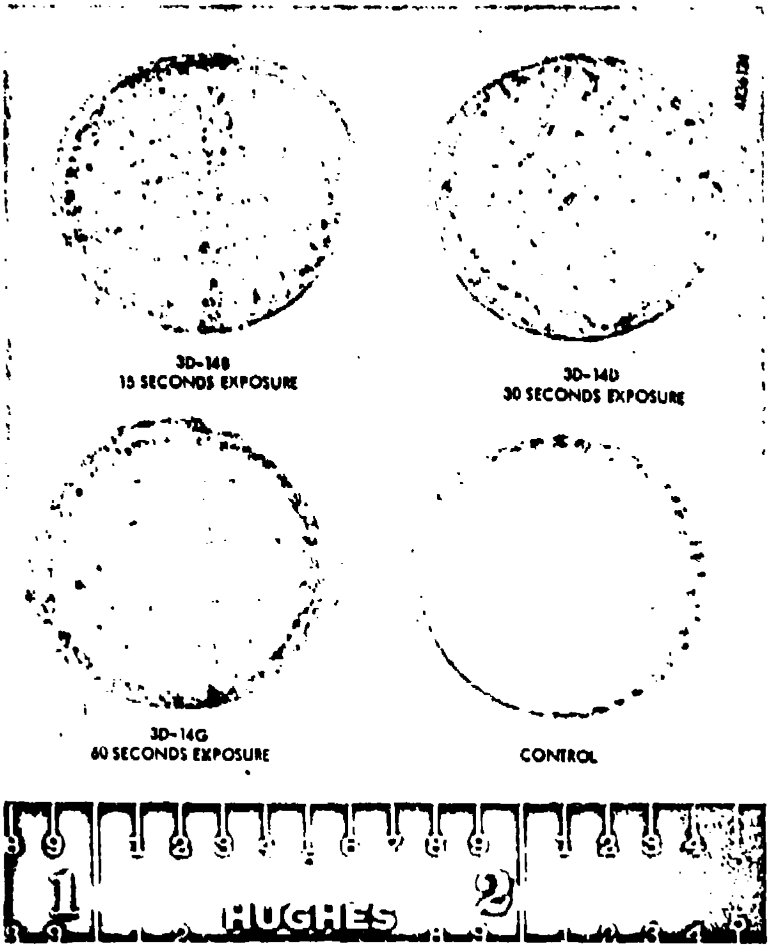

Figure 16. Nomex/glass layer-to-layer angle-interlock Epon 828/menthane diamine; resin content = 43.7 weight-percent.

3D-14

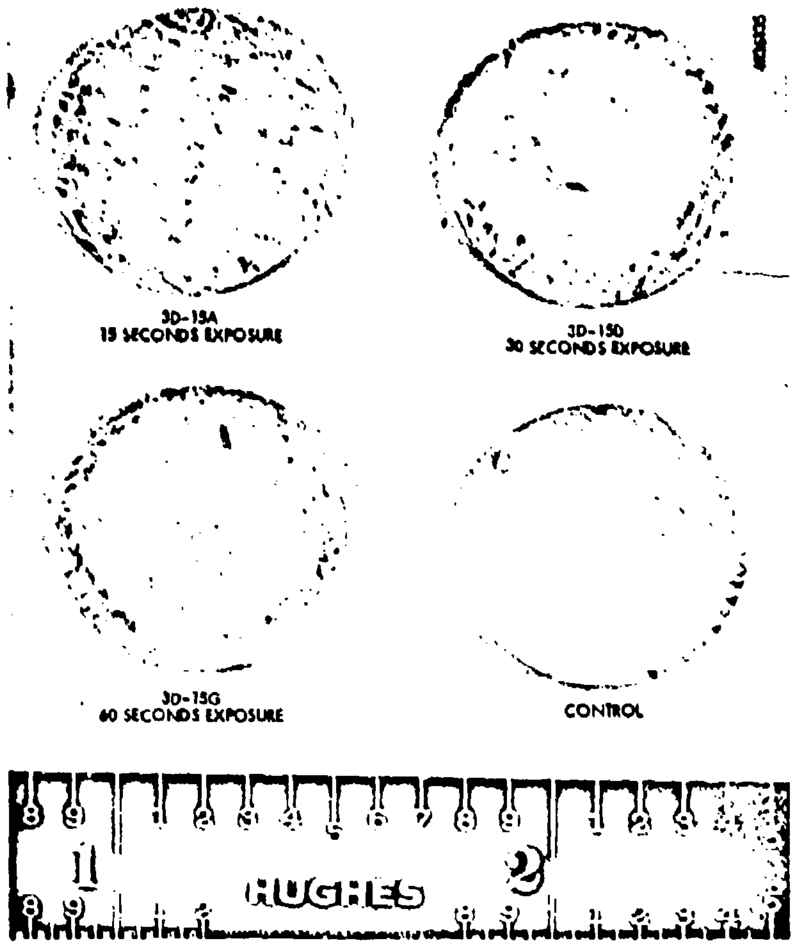

Figure 17. Nomex/glass through-the-thickness, high angle, angle-interlock - Epon 828/ menthane diamine; resin content = 50.2 weight-percent.

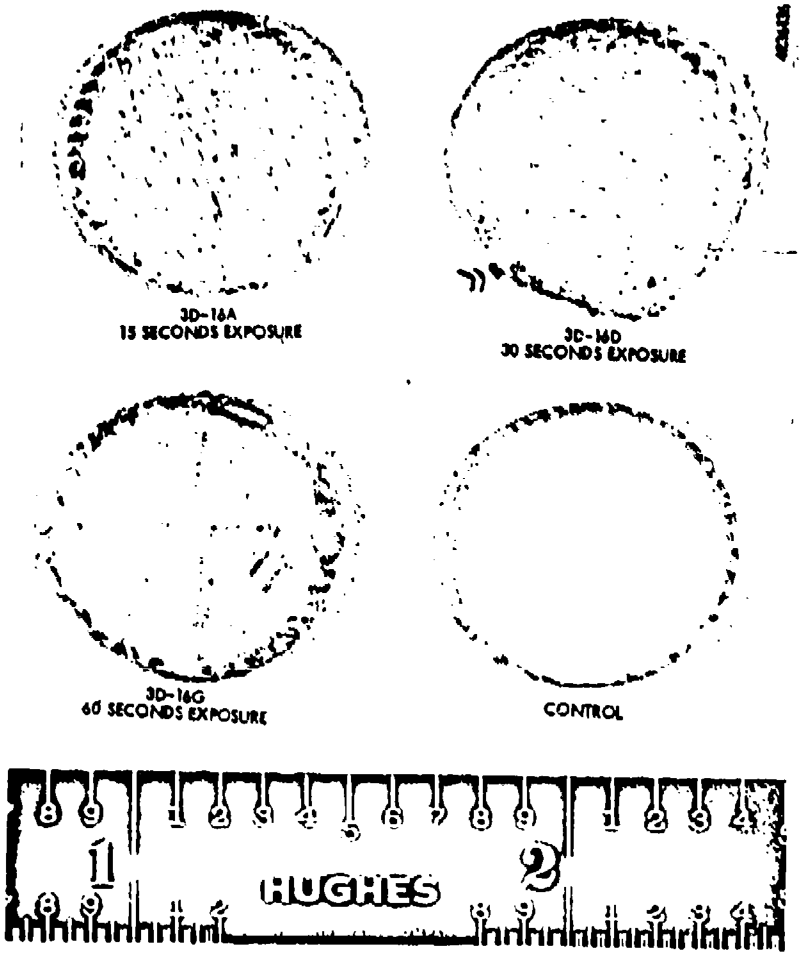

Figure 18. Nomex/glass through-the-thickness, 45° angle-interlock - Epon 828/menthane diamine, resin content = 41.5 weight-percent.

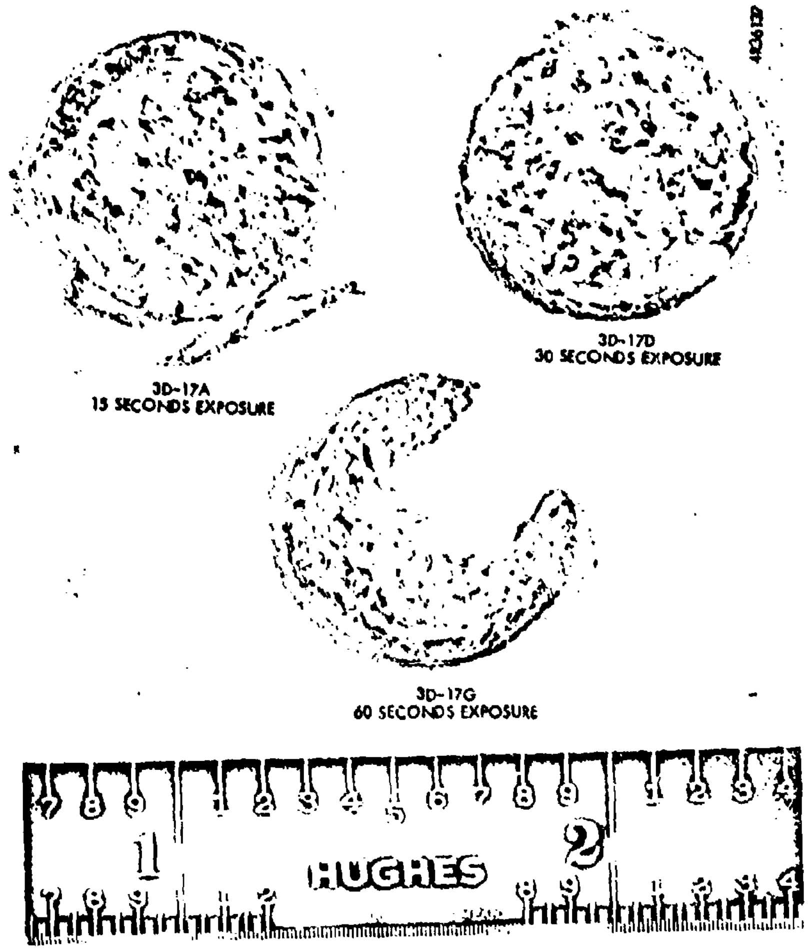

Figure 19. Kevlar 29 layer-to-layer angle-interlock - Epon 828/menthane diamine, resin content = 56.8 weight-percent.

somewhat inferior to the Nomex/glass 45-degree, angle-interlock. It had been felt that increasing the angle warp yarns to a high angle with respect to the surface could result in improved rain erosion resistance. This unexpected result is likely due to the increased fiber content in the 45-degree angle interlock (58.5 weight-percent fibers versus 49.8 weight-percent fibers for the high angle fabric).

The Kevlar 29 composite, as expected, had very poor rain erosion resistance. Similar results obtained previously on unidirectionally reinforced, end-oriented Kevlar/epoxy composites indicated that Kevlar fibers do not yield rain erosion resistant composites.

Combined End-Oriented Structural Specimens

Rain erosion specimens were fabricated which consisted of an end-oriented, rain erosion-resistant surface layer of Dacron/epoxy (52 volume-percent fibers) bonded to a structural substrate of laminated fiberglass epoxy. Three types of specimen were fabricated:

1. Specimen Code: DAG-1
   End-oriented Dacron - 0.150 inch
   Fiberglass substrate - 0.050 inch
2. Specimen Code: DAG-2
   End-oriented Dacron - 0.100 inch
   Fiberglass substrate - 0.100 inch
3. Specimen Code: DAG-3
   End-oriented Dacron - 0.050 inch
   Fiberglass substrate - 0.150 inch

The test results, summarized in Table 7, show that this type of specimen erodes very severely with the failure consisting of failure at the interface between the end-oriented composite layer and the structural substrate. Figure 20 shows typical specimens after only 30 seconds exposure under standard conditions.

Composites From Boeing

Test specimens were prepared from four laminated composites received from Boeing, identified as follows:

1. Polysulfone - 181 E glass laminate (Hughes Specimen Code L-3).

TABLE 7. RELATIVE RAIN EROSION RESISTANCE OF COMBINED END-ORIENTED, STRUCTURAL SPECIMENS

Specimen Code	Material Description	Exposure Time, Seconds	Weight Loss, Mg	Appearance
DAG-1A	End-oriented Dacron/epoxy - 0.150"; fiberglass/epoxy substrate - 0.050"	30	32	Moderately eroded
DAG-1B			21	Moderately eroded
DAG-1C		60	34	Severely eroded near edge
DAG-1D			33	
DAG-2A	End-oriented Dacron/epoxy - 0.100"; fiberglass/epoxy substrate - 0.100"	30	—	Severely eroded near edge
DAG-2B			94	
DAG-2C		60	1058	*
DAG-2D			1024	*
DAG-3A	End-oriented Dacron/epoxy - 0.050"; fiberglass/epoxy substrate - 0.150"	30	692	*
DAG-3B			631	*
DAG-3C		60	370	*
DAG-3D			341	*

*Specimen eroded through to fiberglass substrate

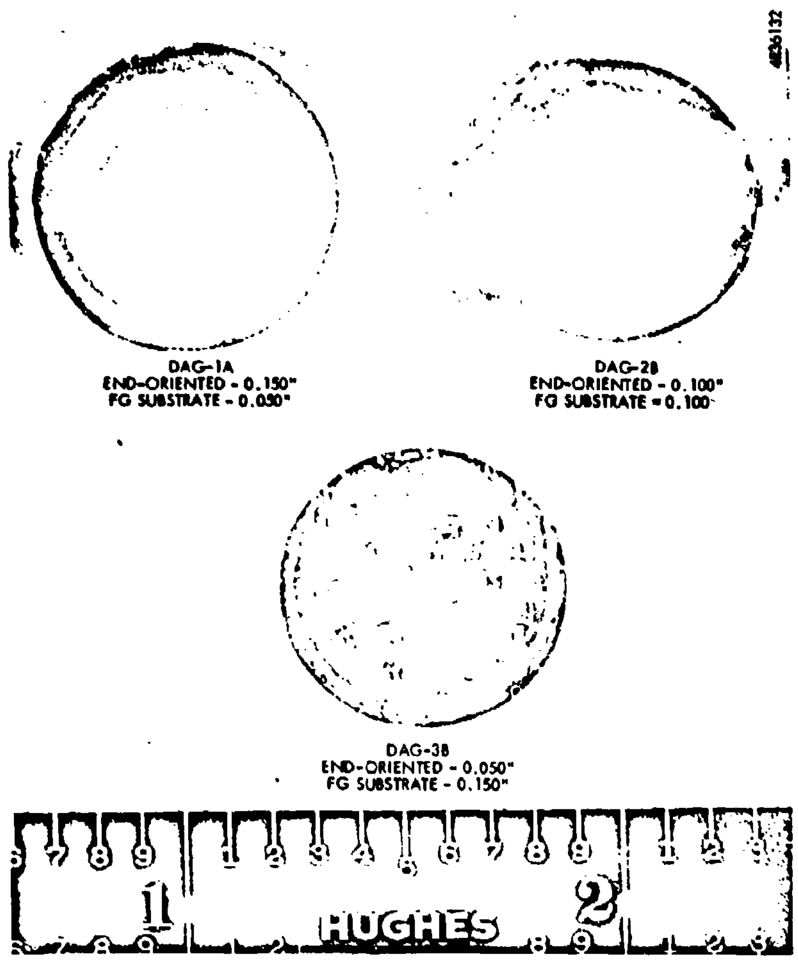

Figure 20. End-oriented Dacron/epoxy with laminated fiberglass epoxy substrate (exposed 30 seconds under standard conditions).

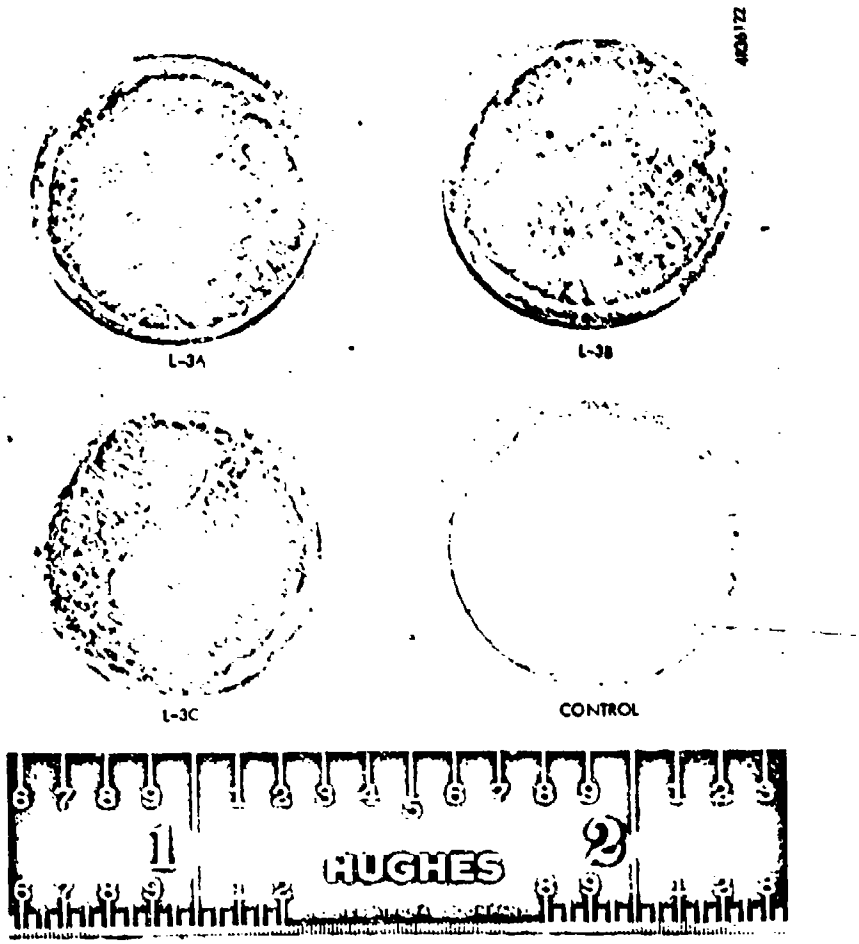

Figure 21. Polysulfone-181 E glass laminate (Boeing).

2. Polysulfone - AS graphite laminate (Hughes Specimen Code L-4)
3. Epoxy-181 glass laminate (Hughes Specimen Code L-5)
4. PKHS-1 (Phenoxy)-181 E glass laminate (Hughes Specimen Code L-6)

Three specimens of each material were tested for 30 seconds each at an impact angle of 90° under standard conditions.

The results, summarized in Table 8, show the polysulfone-AS graphite composite and the phenoxy-181 glass composite to be fairly rain erosion resistant, while the polysulfone-glass laminate and epoxy-glass laminate to have relatively poor rain erosion resistance comparable to that of epoxy-glass laminates tested previously.

TABLE 8. RELATIVE RAIN EROSION RESISTANCE OF LAMINATED COMPOSITES FROM BOEING (30 seconds exposure, 90° impact angle)

Specimen Code	Material Description	Weight Loss, Mg	Erosion Depth, Mils	Appearance
L-3A	Polysulfone-181 E	244	26	Extremely eroded
L-3B	Glass Laminate	282	21	
L-3C		225	19	
L-4A	Polysulfone-AS	117	6	Moderately eroded
L-4B	Graphite Laminate	84	4	
L-4C		124	5	
L-5A	Epoxy-181 Glass	314	28	Extremely eroded
L-5B	Laminate	334	36	
L-5C		318	28	
L-6A	PKHS-1 (Phenoxy) -	106	9	Moderately eroded
L-6B	181 E Glass	95	7	
L-6C	Laminate	106	11	

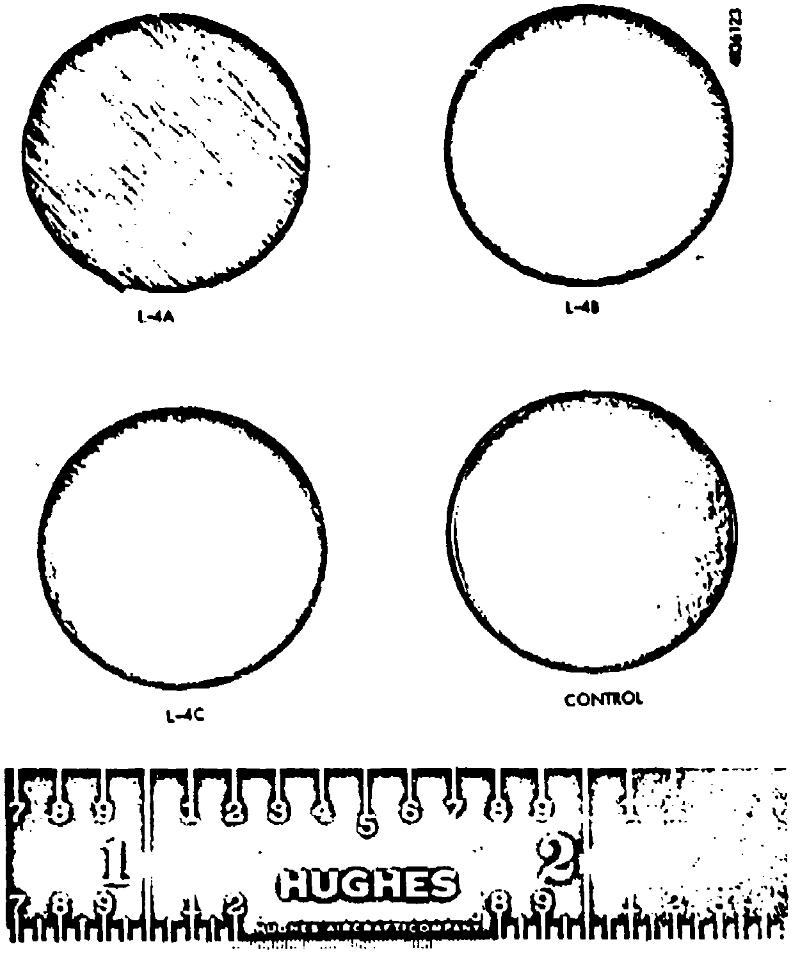

Figure 22. Polysulfone-AS graphite (Boeing).

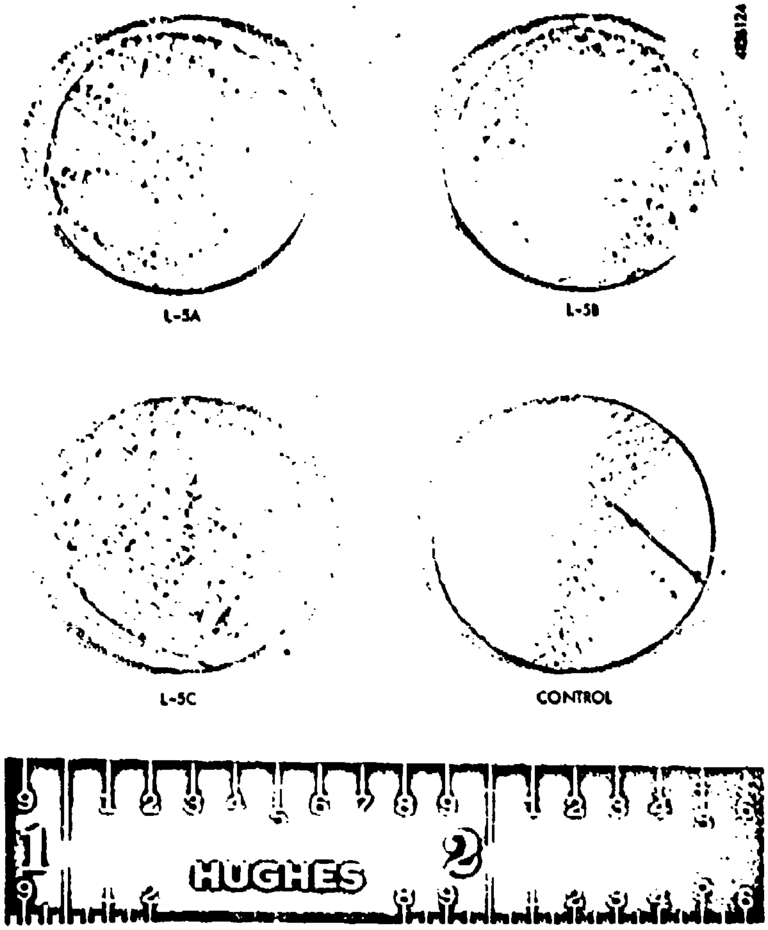

Figure 23. Epoxy-181 glass laminate (Boeing).

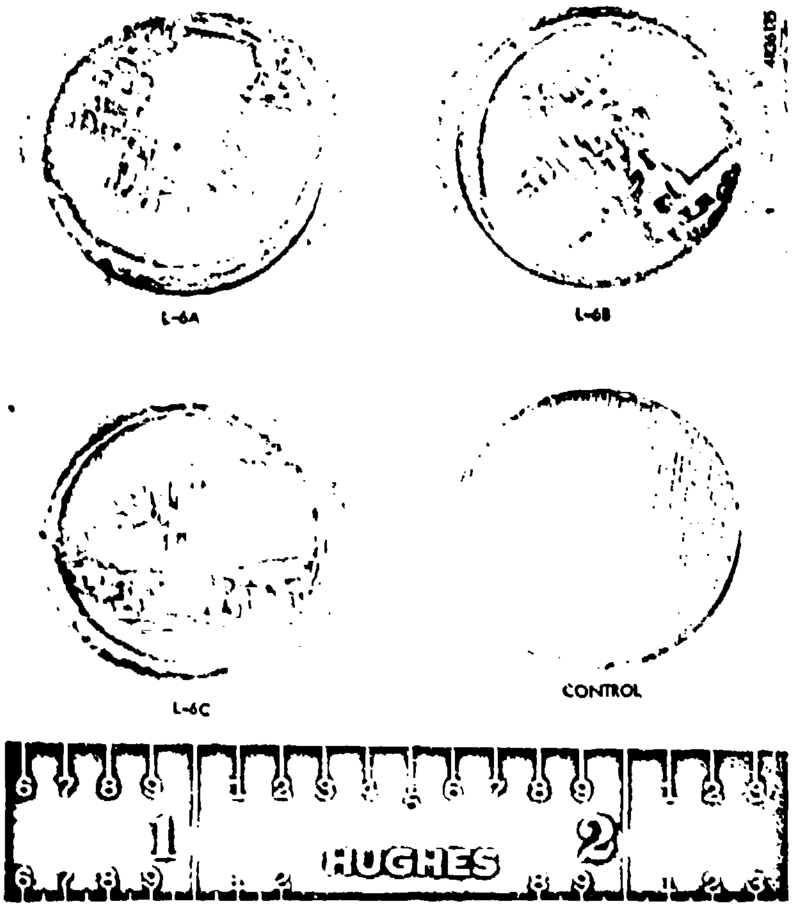

Figure 24. PKHS-1 (phenoxy)-181 E glass laminate (Boeing).

STRENGTH PROPERTIES OF END-ORIENTED NOMEX/EPOXY

As requested by Materials Sciences Corporation, the shear strength and compressive strength properties of end-oriented Nomex/epoxy composites were measured.

Shear Strength

The shear strength in the fiber direction of an end-oriented Nomex/epoxy bar with a fiber content of 50 volume-percent was determined by means of a special shear test fixture. This shear fixture consisted of a quarter-inch diameter hardened steel pin aligned with a corresponding hole in a base plate by means of a suitable bushing. In practice, a disc of the end-oriented epoxy (fibers parallel to axis) 0.70 inch in diameter by 0.200 inch thick is placed on the base plate, the bushing is put in place and the pin inserted in the bushing. The assembly is then placed in a standard test machine and the load is increased until shear failure occurs.

The average value obtained for shear strength was 5.71×10^3 psi with a standard deviation of 0.29×10^3 psi.

Compressive Strength

Compressive strength measurements were made on an end-oriented Nomex/epoxy with a fiber content of 50 volume-percent. The tests were run in accordance with ASTM D695 on cylindrical specimens 0.375 inch in diameter by 0.750 inch long with the fibers parallel to the specimen axis. The results showed the Nomex/epoxy to have a compressive strength in the fiber direction of 31.9×10^3 psi with a standard deviation of 0.28×10^3 psi.

ELECTRICAL PROPERTIES OF MULTIDIMENSIONAL COMPOSITES

Two multidimensional composites were taken for dielectric measurements:

1. No. 3D-14: Nomex/glass layer-to-layer angle-interlock - Epon 828/menthane diamine.
2. No. 3D-17: Kevlar 29 layer-to-layer angle-interlock - Epon 828/menthane diamine.

The dielectric constant and loss tangent of the two composites were calculated from shorted waveguide measurements made at a frequency of 10.0 gHz. The procedure involves measuring the position of a voltage minimum in a shorted waveguide with and without the dielectric specimen contacting the short. This difference in voltage minimum position, the guide wavelength and specimen thickness are used to calculate the dielectric constant and loss tangent of the dielectric material. A full description of this measurement technique is given in section 10.06 of "Handbook of Microwave Measurements," Volume I, Wind and Rapaport, Polytechnic Press, 1954.

The test results were very close for the two materials: the Nomex/glass/epoxy composite No. 3D-14 had a dielectric constant of 3.45 and a loss tangent of 0.019, while the Kevlar 29/epoxy composite has a dielectric constant of 3.50 and a loss tangent of 0.022.

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

Several main conclusions may be drawn from the test results:

1. Multidimensional fabrics, consisting of combinations of polymeric fibers such as Nomex and Dacron and in-plane structural fibers such as glass, yield composites which are far superior in rain erosion resistance to fiberglass laminated plastics. For example, after an exposure of 30 seconds under standard conditions, the rain erosion specimens made from the Dacron-glass angle-interlock fabric suffered less than 20 percent of the weight loss of a typical 181 E glass fabric reinforced laminate, while the corresponding surface recession was only 12 percent.

2. End-oriented composites are far superior to those made from the multidimensional fabrics, even those containing polymeric fibers. For example, typical end-oriented glass-epoxy composites erode, as evidenced by weight loss, only 23 percent as fast as even the best multidimensional composite.

3. Composites consisting of an end-oriented surface layer bonded to a structural substrate fail during rain erosion testing at the interface between the two layers.

Future activities should be concentrated in several principal area:

1. Further development of thin-walled, multidimensional constructions embodying both superior rain erosion resistance and adequate structural properties, in which emphasis will be placed on obtaining improved properties by mathematical analysis.

2. Military aircraft radome applications, present and future, will be reviewed for structural and electrical performance requirements to establish the feasibility of using optimized, thin-walled, multidimensional constructions.

3. Military aircraft radar requirements will also be reviewed to determine the feasibility of using thick-walled, end-oriented constructions in selected applications in which extreme rain erosion resistance is desirable.

4. Additional screening of newly available matrices and reinforcements will be continued by rain erosion testing, measurement of structural properties and by the performance of appropriate analytical studies.

5. Fabrication and testing of a small, conical or ogival radome structure with the optimum combination of rain erosion resistance and structural properties.

APPENDIX

MATERIALS SCIENCES CORPORATION

MSC/TFR/7401

INVESTIGATION OF COMPOSITE MATERIALS WITH
IMPROVED RAIN EROSION RESISTANCE
FOR RADOME APPLICATION

Final Report
January 1974

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INTRODUCTION

The primary objectives of this program have been to organize existing erosion data on composite materials, recommend additional testing required, and then define erosion resistant material designs which will be both resistant to weight loss due to erosion, and possess sufficient in-plane material properties to allow use as a structural material for radome applications.

The work described herein consisted of several interrelated tasks. Initially the erosion data obtained by Hughes Aircraft Co. since 1971 was assembled and organized to ascertain the various parameters which affect the erosion resistance of composite materials. Several areas were discovered which required additional data, and an initial testing program was outlined and recommended to Hughes Aircraft. Some additional tests were recommended for some different test configurations to aid in developing an understanding of the relative merits and/or penalties of having fibers at various angles to the specimen surface.

The program was originally to have had a second test series to further classify assumptions being made in the analysis. However, test scheduling did not permit time for an interim test series. Consequently the specimen configurations recommended at the end of this report must serve a two-fold purpose. Namely, several basic specimen configurations are recommended to determine the effects of having positive and negative angle fiber placements, resulting in greatly enhanced shear capability for the material. In addition, the woven specimens recommended are those which appear best suited for a structural, rain erosion resistant material, and will also fill several information gaps regarding behavior of various 3-D fiber systems. After the tests recommended in this phase of the program are completed, the data should be analyzed and final recommendations made for improved radome material. That is, a final material recommendation is not possible until some further tests are conducted.

SUMMARY OF TEST DATA

The initial task was one of studying the large amount of erosion test data available from the Hughes Aircraft final reports, Reference 1-3. The pertinant data have been reduced to several weight loss graphs which are useful in determining the effect of some of the controllable parameters affecting the erosion resistance of composite materials. One must be cautioned however in that photographs of the specimens must be studied along with the weight loss data. This is true since in some cases large cracks and deep local pitting occurred on the specimen surfaces while seemingly little specimen weight was lost.

Fiber Volume Fraction

When considering a sufficiently erosion resistant composite for structural applications, several questions arise. Since through-the-thickness fibers improve erosion resistance, one needs to know the sensitivity of the erosion resistance to the through-the-thickness fiber volume fraction. In addition, since in-plane structural properties will be increased primarily by reducing the through-the-thickness volume fraction so that in-plane fibers may be added, one needs to know how low the through-the-thickness fiber volume fraction may be reduced and still yield a material with sufficient erosion resistance.

The data plotted in Figure 1 for EPON 828/MPDA Nomex with different fiber loadings shows the data available for answering the above questions. At first appearance, the data for non plasma treated material indicates a substantial reduction in weight loss as the fiber volume fraction increases above 50%. However, photographs of the specimens after test showed deep local pitting, and cracking occurred in most of the specimens with fiber volume fraction over 50%. The data for the plasma treated fibers shows little or no effect of fiber volume fraction on the erosion resistance. Very little data exists for fiber volume fractions around 50% for both plasma treated and untreated fibers. Consequently more test data in the 50% volume fraction area was recommended. To determine if the high fiber volume fractions do or do not significantly improve erosion resistance.

The recommended tests for both plasma treated and untreated Nomex fibers in an EPON 828/MPDA matrix with a fiber volume fraction around 50% were completed. The data, added to previous data, are shown in Figure 2. As can be seen, the apparent significant improvement in erosion performance at fiber volume fraction 50% does not exist when the latest data are included. However, a general decrease in weight loss with increasing fiber content does exist, and the plasma treated material appears to show a slight improvement in performance over the non plasma treated material. Figure 2 indicates that a reasonable trade-off exists between fiber volume fraction through-the-thickness and erosion performance.

Weight Loss Versus Exposure Time

Examining Figure 2 one sees that weight loss does not appear to be a linear function of time. Since a large body of data exists with a non common exposure time base, it is difficult to make comparisons without normalizing the weight losses to a common time base. Initially, a linear normalization was assumed, but it was recommended that tests be conducted with weight losses measured as a function of exposure time to provide a means of normalizing the data for comparison purposes. The results of that series of tests are plotted in Figure 3. As shown in Figure 3, the erosion weight loss can indeed be approximated as a linear function of exposure time for the exposure times considered, at least for the EPON 828/MPDA Nomex material. Non linear effects should be expected for very short and perhaps for very long test exposure times.

Impact and Fiber Angle Effects

The angle of the rain drop velocity vector to the specimen surface, and the angle of the through-the-thickness fibers to the specimen surface could produce significant erosion performance effects.

Figure 4 shows the data on the effect of impact angle on the erosion resistance of EPON 828/MPDA Nomex. For the data of Figure 4 the raindrop velocity vector was parallel to the fibers at all times, while the angle of the surface of the specimen to the raindrop velocity vector was varied. Several interesting conclusions can be

drawn from these data. For a given composite material there was very little effect of the angle of impact on the erosion weight loss. However, the material to material variation was significant.

Examining the data for V_f = 35.2% and 35.4% in Figure 4, one finds a factor of 4 to 5 difference in weight loss. This difference may be attributed to possibly two factors. Testing conditions may have varied and affected the results. If tests of 35.2% and 35.4% materials were run during the same testing series, one would have expected the test conditions to be fairly consistent. However, if a significant amount of time lapsed between each series of tests, the test conditions may have altered slightly and could significantly affect the results. A more likely source of variability is the batch to batch variability of the material properties. If this latter effect dominated the data, then one must be extremely cautious when comparing test results. Ideally the test results should only be compared for specimens originating from the same initial billet of material. It is recognized, however, that for large testing programs it is not always possible for one billet of material to supply the required number of specimens. As an indicator of possible billet to billet variations, it is recommended that a few mechanical property tests be performed for each billet of material. For example, differences in short beam shear test results or compression test results could indicate mechanical property variations between different materials which may indicate different erosion weight loss behavior for the two materials.

Figure 5 shows the effect of impact angle on the erosion weight loss for IPCN 838/MPDA-ECG Glass. For these data the fibers were normal to the specimen surface while the impact angle was varied. As can be seen, there is little effect of impact angle in an adverse sense. The data appear to indicate an increase in erosion resistance with increasing angles. Due to the apparently good performance of Nomex fibers, it was recommended that the series of tests be repeated with 1-D specimens of Nomex fibers. In addition, tests were recommended with configurations of impact surface normal to the raindrop velocity vector, but varying fiber angles to the

specimen surface. Figures 6 thru 8 present the results of those tests.

For impact on a specimen with fibers oriented at 90° to the surface, Figure 6, the erosion resistance improves as the angle of impact decreases. However if the angle of impact is held at 90° to the specimen surface and the fiber angle varied, Figure 7, one finds a definite decrease in erosion performance for fiber angles below roughly 70°. Thus it is desirable to maintain the fiber orientation to the surface over 70°. The test results in Figure 8 were for specimens which had the fibers oriented parallel to the raindrop velocity vector but the surface cut at various angles. These results indicate that one could tolerate a surface angle down to perhaps 60°.

Unfortunately throughout the above tests, the angle of the centrifugal force vector to the specimen surface was not defined. Orientation of the specimen surface, and hence fibers, relative to the centrifugal flow of the raindrop during and after impact could influence damage mechanisms and hence affect erosion resistance. Future tests should include controlled specimen orientation to determine the magnitude of this variable.

One recommended series of tests were not performed, namely the $\pm\theta$ laminate tests. In attempting to generate fiber configurations which provide both erosion resistance and in-plane properties, most configurations considered have a balanced symmetric pattern. For balanced materials with fibers at an angle to the surface, the shear strength is greatly improved, and the microstructure is significantly different from an aligned or 1-D composite. Thus, tests of specimens made up of laminae of fibers in $\pm\theta°$ configurations with raindrop impact normal to the surface are required to assess microstructure and structural property effects on the erosion weight loss. Since these tests were not conducted, future test programs of fundamental property effects should include a series of $\pm\theta°$ laminate specimen tests.

One can draw the following conclusions from the existing unidirectional composite test data: Namely the best erosion resistance was obtained for material configurations with the fibers oriented between 70 and 90 degrees to the specimen surface. Fibers oriented at 90 degrees to the surface offer the benefit of further weight loss decreases for raindrop impacts at an angle to the surface different than 90 degrees.

IN-PLANE MECHANICAL PROPERTIES

The introduction of in-plane fibers and/or diagonal fibers are required in order to develop in-plane properties which are sufficient to prevent failure from structural loads. A trade-off thus exists between erosion performance and in-plane structural properties. The primary variables available for controlling in-plane properties are the volume fraction and type of fibers placed in-plane for 3-D material, and the weaving angle and fiber volume fractions for 4-D omniweave and angle interlock material.

The MSC - X-CAP computer code, described in Appendix A, has been used to estimate in-plane properties for several different fiber systems: all Nomex fibers in a 4-D weave configuration, all Nomex fibers in a 3-D weave, a 3-D weave with Nomex fibers in the through-the-thickness direction and E-glass fibers in the two in-plane directions; an angle interlock material with Nomex fibers in the diagonal directions, the warp direction, and E-glass fibers in the two in-plane directions, the stuffer and fill directions, and finally an angle interlock material with Kevlar 49 fibers. (Formerly PRD-49).

In plane property estimates during this study were confined to a fixed range of fiber volume fractions. Thus, in one sense, a direct comparison between the different material configurations could be made. As described in the geometry section, the theoretical maximum prism volume fractions can be determined. However, a unit cell model must assume a prism packing density, which is a function of the weaving process itself. Consideration of the actual fiber volume fractions obtainable must wait until several weave configurations are manufactured and fiber volume fractions determined.

For the 4-D material the in-plane properties were determined parametrically by varing the total fiber volume fraction from 0.30 to 0.60, and also varing the projected fiber angle on the face of the unit cell from 35 to 75 degrees. Thus both total fiber content and weaving angle were varied.

The properties for the two 3-D configurations were determined for the following conditions. The total fiber volume fraction was held constant at 60%. The through-the-thickness fiber volume fraction was varied from 30% to 60% with the

remaining fiber content being equally distributed in the two in-plane directions. That is, for a through-the-thickness fiber volume fraction of 40%, there was a total of 20% fibers in the in-plane directions, 10% in the "X" and 10% in the "Y" directions (the Z direction being through-the-thickness).

For the angle interlock material the total fiber volume fraction was again held at 60%. The stuffer and filler yarns were assumed to be E-glass with fiber volume fractions in each direction of 5-15%. The remaining fibers were Nomex fiber bundles oriented at varing angles from 45 to 85 degrees. In addition, an all Kevlar-49 angle interlock material was examined. Fiber and matrix properties used in the analysis are listed in table 1.

Figure 9 shows the variation of in-plane modulus with fiber volume fraction and weaving angle for a 4-D Nomex composite. As can be seen, for the practical range of fiber angles the in-plane modulus is relatively insensitive to weaving angle, but is very sensitive to the fiber volume fraction. Figure 10 gives the corresponding results for the two 3-D weave configurations. Note that the all Nomex weaves result in roughly the same in-plane stiffness for fiber volume fractions of 60%, and that the Nomex in-plane volume fraction affects the in-plane modulus only slightly. The E-glass fibers in-plane offer the most significant increase in in-plane modulus and, hence, offers a stiffer shell material.

Figure 11 shows the in-plane and through-the-thickness moduli of angle interlock material as functions of the interlocking fiber angles. Again the in-plane moduli are insensitive to the weaving angles, indicating that the best control of in-plane modulus may be simply the quantity of in-plane E-glass fiber content.

Kevlar-49 angle interlock was examined, figure 12, with much the same result. The very high tensile modulus of Kevlar-49 interlocking fibers could not contribute significantly to the in-plane properties since the fiber is very anisotropic, with a very low shear modulus.

Stiffness, however, governs buckling modes of failure, and not strength modes of failure. Thus, some estimates of the in-plane strength of the different materials are required.

The MSC - X-CAP computer code computes average fiber bundle and interstitial matrix stress states for any given applied loading conditions, as well as compute effective elastic constants for a given unit cell of material. Thus, given fiber bundle tensile and shear strengths, as well as matrix strength, it is possible to predict the composite strength.

Due to the probable thin sections which will be required, only several unit cells will be present through the thickness of the material. The strength estimates must therefore be viewed as approximate since edge effects will affect measured strength values. The results are nevertheless significant since trends in strength with the fiber volume fractions and fiber orientations will be predictable.

Figure 13 shows the in-plane strength of 4-D all Nomex weave with EPON 828/MPDA matrix as a function of fiber volume fraction and weave angle. A combined stress failure criteria (fiber bundle axial stress and shear stress) was used to predict strength. The assumed fiber bundle shear strength of 5000 psi was found to dominate the failure stress prediction. As expected, orienting fibers in the through-the-thickness direction decreases the in-plane strength. Although the in-plane strength is not exceptionally large, the 4-D weave offers several advantages over 3-D weaves, see Appendix B.

Figure 14 has been constructed to show the in-plane strength of 3-D all Nomex material, assuming that, due to curvature or manufacturing errors, the in-plane fibers are at some angle to the plane of the material. These results are quite significant since the ultimate material use will be in curved shells. It is reasonable to expect that the in-plane fibers will not be truly in-plane throughout significant regions of material. As can be seen in Figure 14, the attractive fiber direction properties of the 3-D weaves drop off rapidly with increasing fiber orientations. Thus, if high strength is a severe requirement, manufacturing processes must be very carefully controlled.

Figure 15 gives similar results for a 3-D material with E-glass in the plane of the material, showing a similar drop-off in strength with increasing fiber orientation.

Figure 16 presents the effect of orienting a 4-D weave material slightly out of the plane of material. As can be seen the 4-D material shows little change in strength as compared to the 3-D fiber systems, which can be advantageous in many design configurations. It has been shown, Reference 1, that the largest tensile strength of the 4-D weaves is in the direction of any one of the 4 fiber orientations. The various merits of X-D weaves are explaned in Appendix B.

The in-plane strength of the Nomex/E-glass angle interlock material is shown in Figure 17. Note that there is a small but not significant dependence of in-plane strength upon weaving angle.

MATERIAL DESIGN FOR STRUCTURAL AND EROSION REQUIREMENTS

The objective of this phase of the study is to plan an experimental program to obtain the information required for the design of a fiber reinforced plastic material for aircraft radome applications. Structural requirements for this application require that some of the fibers used must be oriented in the local plane of the shell wall. Evaluation of the experimental results obtained during this program indicates that through-the-thickness fiber orientations are highly desirable for erosion resistance. Thus a logical material configuration would have an orthogonal planar array of good structural fibers such as glass, integrated with through-the-thickness fibers of Nomex, or perhaps Dacron. This combination can, in concept, be obtained by bonding an outer layer of unidirectional normal fibers to an inner, structural layer of glass reinforced plastic. This configuration would appear to be susceptible to serious delamination problems as a result of the dynamic loading imparted by the impacting droplets, and of the necessarily small layer thicknesses. Although a test of such a configuration may be desirable, it appears likely that a three directional orthogonal woven reinforcement will yield improved overall performance. The question of the types of fibers to be used and the relative amounts of each in the three different directions is discussed elsewhere. The question treated here is that of defining the available range of properties as limited by the maximum possible fiber volume fractions for different weaves.

The unit cell for a three-directional, orthogonal weave is shown in Figure 18. The unit cell is the basic repeating volume element in any weave of regular geometry. For this 3-D case it may be divided into prismatic regions which are cylinders parallel to each of the three orthogonal directions. Unidirectional fibers can then be oriented along each of these prisms without any interference problems. Such a geometry defines the potential fiber volume fractions which can be achieved with straight fiber arrays. Of course in a weaving process, fiber crimping or bending can occur, causing fibers to be located in regions outside the prism volume regions shown in Figure 18.

Thus, several volume fractions are of interest. First, the maximum prism volume fractions. These are plotted in Figure 19, showing the through-the-thickness value as a fraction of the in-plane value, assuming equal fiber amounts in each of two in-plane orthogonal directions. The maximum total fiber volume fraction is found from this by recognizing that a fiber bundle can pack as circular cylinders in an hexagonal array for greatest volumetric efficiency. In practice the actual number for a set of straight fibers will be reduced because both the actual prisms and the actual bundles within the prisms will pack at some 60% to 75% of theoretical values. Measurements on 3-D carbon and graphite weaves has shown a practical total fiber volume fraction equal to about 50% of theoretical. The curvature effect will increase this last number. Thus, as an example, a curve is presented for a case in which the actual prism volume fraction is 70% of the theoretical maximum. The local fiber volume fraction is 75% of the theoretical maximum and the fiber volume increase due to curvature is represented by a factor of 1.2.

The 3-D orthogonal weaves do little to improve the shear resistance along the principal elastic planes. For this reason an angle weave of some sort is considered to be a desirable possibility. This cannot be established at this point because of the lack of experimental erosion data for materials having fibers inclined in two directions making equal and opposite angular directions with the surface. Several possible angle weave constructions are shown in Figure 20. The unit cell for a full depth angle interlock weave is shownin Figure 21. For this type of weave the prism volume fraction of the angled prisms has been computed and is shown in Figure 22 as a function of the desired in-plane volume fraction. Again this latter quantity is assumed to be composed of equal volume fractions in each of two orthogonal directions. The angle volume fractions are independent of the angle of orientation (with the exception of 0° and 90°) if the ratios of prism sizes in the different directions are not constrained, but are permitted to take on any values. This implies the availability of continuous selection of yarn deniers. In practice discrete angles will be required to attain these values because of the limits on and the discrete number of filaments in a commercial yarn which is to be

used in this weaving. Here however the initial choice will be made for the purpose of designing experiments to obtain the erosion data required.

The sample of angle interlock supplied to MSC was examined to determine the fiber content. As an approximation, all fibers were assumed to be 1100 denier dacron, neglecting the small content of glass. Based on 288 ends/inch, one finds that the warp fiber volume fraction is 51% and the stuffer and filler volume fractions are roughly 13% each, resulting in a total fiber volume fraction of 77%. To check this figure, the weight of the piece of material was calculated, knowing the density of dacron and assuming 77% fiber volume fraction. The theoretical weight was found to be 1.67 ounces, which compares very well with the measured weight of 1.6 ounces. Thus, the sample of angle interlock appears t be a good quality weave and should be included in the testing program.

It can be seen from a comparison of Figures 19 and 22, that higher total fiber volume fraction is to be obtained in the 3-D weaves. However the improvement in material performance obtained by placing fibers in additional directions suggests that experiments with some representative angle interlock weaves are desirable. An illustration of the possible effect is provided by the simple comparison between a unidirectional layer subjected to a static compressive force at an angle to the fiber direction and the same load applied to a symmetric biaxial material in which half of the fibers are oriented at each of two equal but opposite angles to the applied load direction. This result is shown in Figure 6 for a Kevlar-49* epoxy composite.

It should also be remarked that the off-axis test data obtained for erosion of other fiber composites may not be applicable to Kevlar 49, since this fiber is highly anisotropic. It may well behave in a better fashion for off-axis impact because the fiber anisotropy will result in additional energy absorbing failure modes.

* Formerly PRD-49

CONCLUSIONS

An initial analytical evaluation of the available erosion data for fiber reinforced plastics has been performed. The aim of this analysis was to obtain an understanding of materials which are both erosion resistant and useful for structural application. Obviously, the mechanics of erosion are complex and beyond the scope of this study. In this first phase of the analytical program, the objective was to evaluate and correlate available experimental data and recommend necessary additional tests. A series of recommended materials, having multi-directional fiber orientation, are described in the following section of this report.

The results of the experimental and analytical studies to date can be summarized as follows. The erosion test data indicate that for 1-D composites the best orientation of the fiber is at 90 degrees to the material surface. Plasma treated Nomex fibers offer a slightly improved erosion resistance over untreated fibers. There is a small effect of fiber volume fraction on the erosion resistance for fiber volume fractions between 40 and 80%. Thus the through the thickness fiber volume fraction can be reduced below 70-80% to allow placement of in-plane fibers for in-plane properties, without a severe sacrifice in erosion performance.

Angle interlock materials have not been tested to date. The placement of fibers at positive and negative angles to the surface greatly increases the through the thickness material properties. Hence there is reason to believe that there will be a significant improvement in erosion performance for these materials. In addition, fibers such as Kevlar 49, which are highly anisotropic, may actually exhibit higher erosion resistance when used in a $\pm\theta$ configuration as opposed to an all 90° configuration.

In-plane property predictions indicate that for a 3-D orthogonal material the only significant improvements in in-plane properties occur if glass fibers are placed in-plane, with Nomex fibers placed through-the-thickness. The 4-D materials such as omniweave do not appear to offer significant

structural property improvements over 3-D orthogonal materials, particularly when one considers the additional costs involved in fabricating an omniweave mat.

It was found that the in-plane properties of the angle interlock material are not sensitive to the angle of the interlocking fibers. For Nomex warp fibers and glass stuffer and filler fibers, the Nomex does not contribute significantly to the in-plane properties. For an all Kevlar-49 material, the low shear modulus of the Kevlar-49 fibers results in little contribution of the warp fibers to in-plane properties. Consequently, one would conclude that the best angle-interlock configuration would be to place the fiber in the direction of best erosion resistance. In-plane properties would be obtained simply through the addition of a sufficient quantity of stuffer and filler fibers to obtain the required properties.

The above conclusions were based upon the analysis and evaluation of erosion test data obtained by Hughes Aircraft Co. over the past several years. The question of the possible merits of material configurations using other fiber or matrix materials has not been treated. Treatment of other possible configurations would require the formulation of an analytical model interrelating material structure and properties. A model of this type would address the problem of determining which material configuration could best meet all of the structural design requirements, as opposed to determining simply the strongest or stiffest material configuration.

RECOMMENDATIONS

At this point in the program, it is highly desirable to obtain erosion test data on a series of specimens which systematically evaluate several of the important parameters in the design of multi-directional fiber reinforced materials. However, the present Hughes program does not have the time or the resources for such a test series. Hence it is desired to define a limited series of tests which represent the best engineering estimate of configurations which will possess good in-plane mechanical properties, along with good erosion resistance. A second series of specimen configurations are also described. These are materials which should offer good erosion resistance, and perhaps superior resistance, but insufficient data currently exists to categorize these material as prime candidates for this test series.

It should also be noted that the X-D materials which are woven are expected to be more readily, and economically, adapted to structural configurations, than the 3-D orthogonal materials. (An exception to this case would result if unidirectional materials can be bonded to a substructure as discussed earlier.) Because of the desirable feature of the woven reinforcements, tests are recommended to improve our understanding of the behavior of such materials.

In all cases, erosion testing should include, as before, several specimens at each test conditions. Testing should include weight loss at 30, 60 and 120 second exposure times with the raindrop velocity vector oriented at several angles to the specimen surface. Thus the effect of employing the given material throughout a radome surface will be determined.

If we draw upon the available test data, the most promising specimen configurations appear to be the 3-D orthogonal weaves, utilizing NOMEX fibers through the thickness. A 3-D orthogonal material should be woven for test. E-glass fibers should be used in the two in-plane directions, and NOMEX fibers in the through-the-thickness directions, the number of fibers should be controlled such that the in-plane fiber volume fractions, E-glass, are approximately 10% each. The NOMEX fiber volume fraction should be maximized to the best available weaving capability. Thus, a high

through-the-thickness fiber volume fraction will be obtained.

The second material recommended for testing is an angle interlock material similar to the existing sample utilizing Dacron. NOMEX fibers should be used for the warp fibers and E-glass used as the stuffer and filler fibers, except for the two upper layers of stuffers and filler fibers, which should be NOMEX. Since fibers nearly normal to the surface appear to offer the best erosion resistance, the warp angle should be controlled to yield a final weave with a warp angle of 60 to 80 degrees (90 degrees being through-the-thickness).

The third test configuration is a through-the-thickness angle interlock material with the same fibers as the second material. Since optimum fiber packing may not be achieved in the second material, due to trying to control the warp angle, the third material compromises the warp angle to achieve maximum fiber packing. Namely, the warp angle will be 45 degrees, similar to the existing dacron angle interlock material which has excellent fiber packing densities.

The fourth material recommended for testing is a layer-to-layer angle interlock material, again utilizing the same fiber choices as in material two. Weave manufacturers feel that the layer to layer angle interlock material can be woven with higher fiber volume fractions than the through-the-thickness angle interlock materials. In addition, interlocking each layer of material could potentially produce better erosion resistance of the exposed stuffer and filler yarns and hence result in better material erosion resistance.

The fifth and last material recommended for testing at this time is a through-the-thickness angle interlock material with a warp angle similar to material two. However, the fibers in all directions should be KEVLAR-49. The high degree of anisotropy of the Kevlar fibers indicates that this material may show improved erosion resistance when utilized at some angle to the specimen surface.

The above materials recommended for testing are described in Table 2. An additional series of tests is described in Table 3 for possible future consideration. The purpose of the second series of tests is to examine the effects of some of the controllable properties of the 3-D weaves on the material erosion resistance.

Naturally some refinements to the second series of tests could be made once the results of the first series become available.

The results of those recommended tests may identify an effective material for the radome application. In any event, the data obtained should be valuable in establishing criteria for choosing among the variables considered and designing the best possible materials of this class. It is recommended that this subsequent evaluation of data be performed to complete the program initiated herein. It must be emphasized, however, that the number of variables are large (only a limited number have been treated herein) and our understanding of the mechanics of erosion is inadequate. The capability to design structural materials for resistance to increasingly severe erosion environments does not exist. Further basic studies which combine practical objectives with a rational understanding of the basic factors involved are strongly recommended.

REFERENCE

1. "Development of Composite Construction With Improved Rain Erosion Resistance", B.G. Kimmel, NASC Final Report - p 71-76. March, 1971.

2. "Development of Composite Constructions With Improved Rain Erosion Resistance", B.G. Kimmel, NASC Final Report - p , 1972

3. "Development of Composite Construction With Improved Rain Erosion Resistance", B.G. Kimmel, NASC Final RIport - p 73-43, Jan. 1973.

4. "Advanced Hardened Antenna Window Materials Study III" Edited by J.P. Brazel, AMMRC - CTR - 73 - 26, July 1973.

5. Hashin, Z., "Theory of Fiber Reinforced Materials," NASA CR-1974, March, 1972.

6. Hashin, Z. Rosen, B.W., "The Elastic Moduli of Fiber Reinforced Materials," Journal of Applied Mechanics, Vol. 31, p. 223, 1964.

TABLE 1

Constituent Material Properties Used In Analysis

	NOMEX*	E-GLASS*	KEVLAR-49	EPON 828/MPDA*
Modulus $\times 10^6$ PSI				
Axial	2.8	10.5	19.0	0.46
Transverse	2.8	10.5	1.42	0.46
Poisson's Ratio				
ν_{LT}	0.25	0.25	0.20	0.25
ν_{TT}	0.25	0.25	0.30	0.25
Shear Modulus $\times 10^6$ PSI				
G_{LT}	1.12	4.20	.27	0.184
Strength				
Axial - KSI	80	300	200	10
Shear - KSI	5	5	6	5

* Isotropic

TABLE 2

RECOMMENDED MATERIALS FOR TESTING

NO.	WEAVE	THROUGH-THICKNESS FIBERS	IN-PLANE FIBERS	VOLUME FRACTIONS	COMMENTS
1	3-D Orthogonal	NOMEX	E-GLASS*	Approx. 5:1:1	Max through thickness V_f required with approx. 10% V_f in in-plane.
2	Hi-Angle-Angle Interlock (60°-30°)	NOMEX	E-GLASS*	Best Possible	Weaves Similar to Dacron sample required with approx. 288 ends/inch.
3	Angle Interlock (45°)	NOMEX	E-GLASS*	"	"
4	Layer-to-Layer Angle Interlock	NOMEX	E-GLASS*	"	"
5	Hi-Angle Angle Interlock (60°-80°)	KEVLAR-49	KEVLAR-49	"	"

*Except two layers of yarns at specimen upper surface which will be Nomex yarns.

TABLE 3

RECOMMENDED MATERIALS FOR FUTURE TESTING

WEAVE	THROUGH THICKNESS FIBERS	IN-PLANE FIBERS	COMMENTS
2-D $\pm$ θ	NOMEX	NONE	$\pm\theta$ Laminates
3-D Orthogonal	KEVLAR	KEVLAR	V_f Ratio 5:1:1
Hi-Angle Interlock	NOMEX	E-GLASS	Tested at various impact angles
45° Angle Interlock	NOMEX	E-GLASS	" " " "
Hi-Angle Angle Interlock	NOMEX	E-GLASS	Tested as above, with optimized stuffer & filler yarns to maximize total fiber content.

FIGURE 1 EFFECT OF FIBER VOL. FRACTION ON EROSION - END ORIENTED EPON 828/MPDA - NOMEX

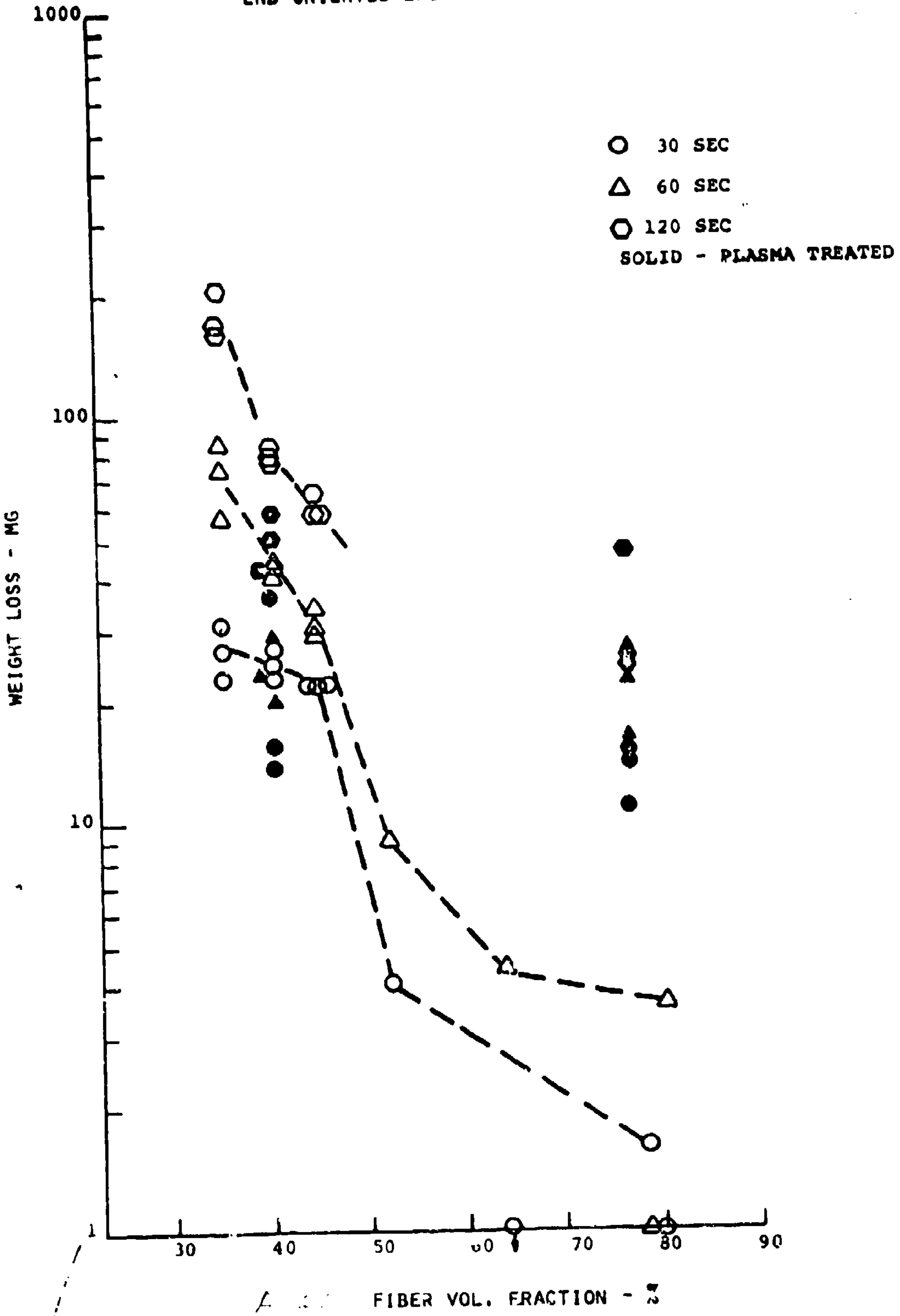


FIGURE EFFECT OF PLASMA TREATMENT AND FIBER VOL. FRACTION ON EROSION

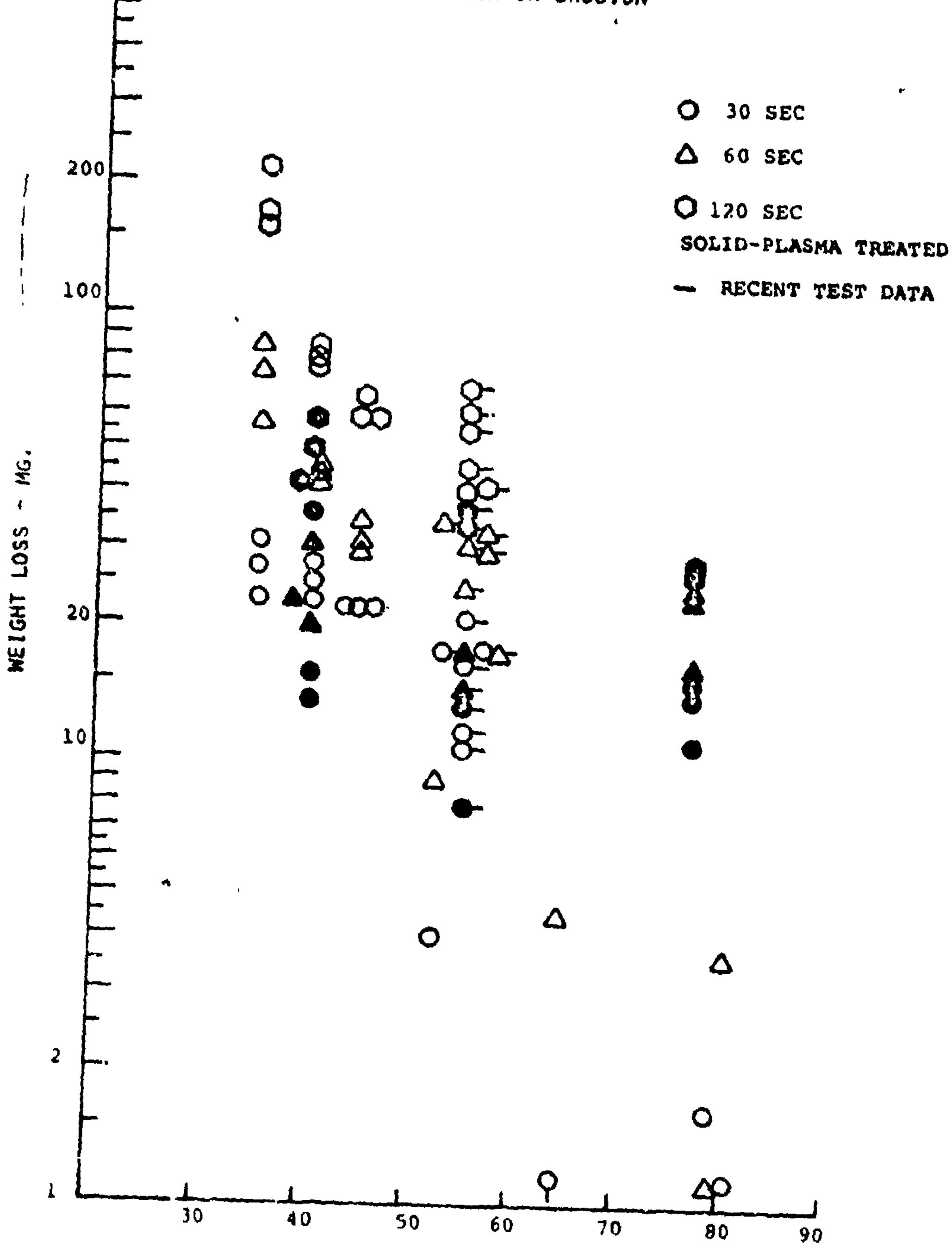


FIGURE 3 WEIGHT LOSS VS TIME FOR FIBERS AND IMPACT AT 90° TO SURFACE

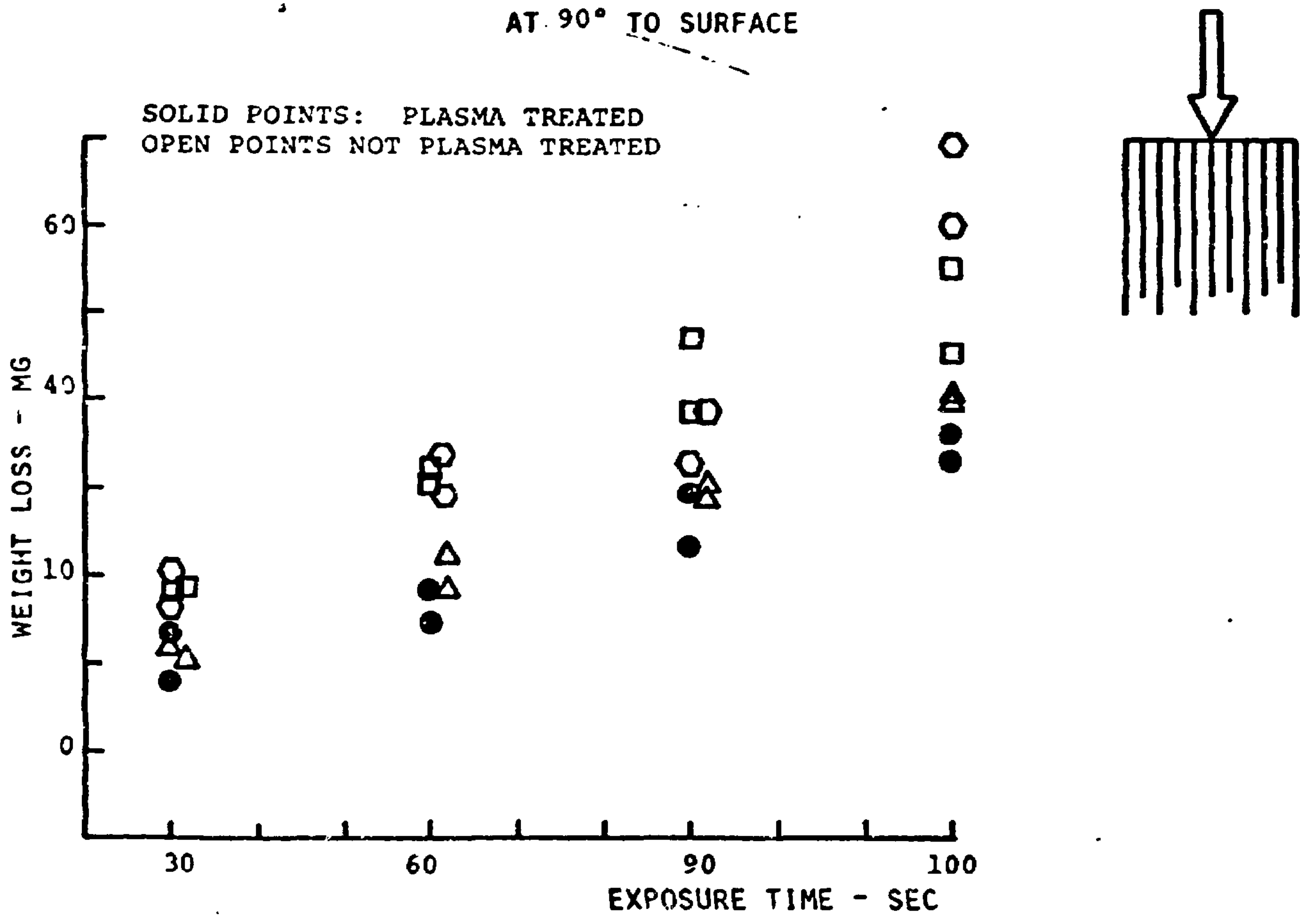
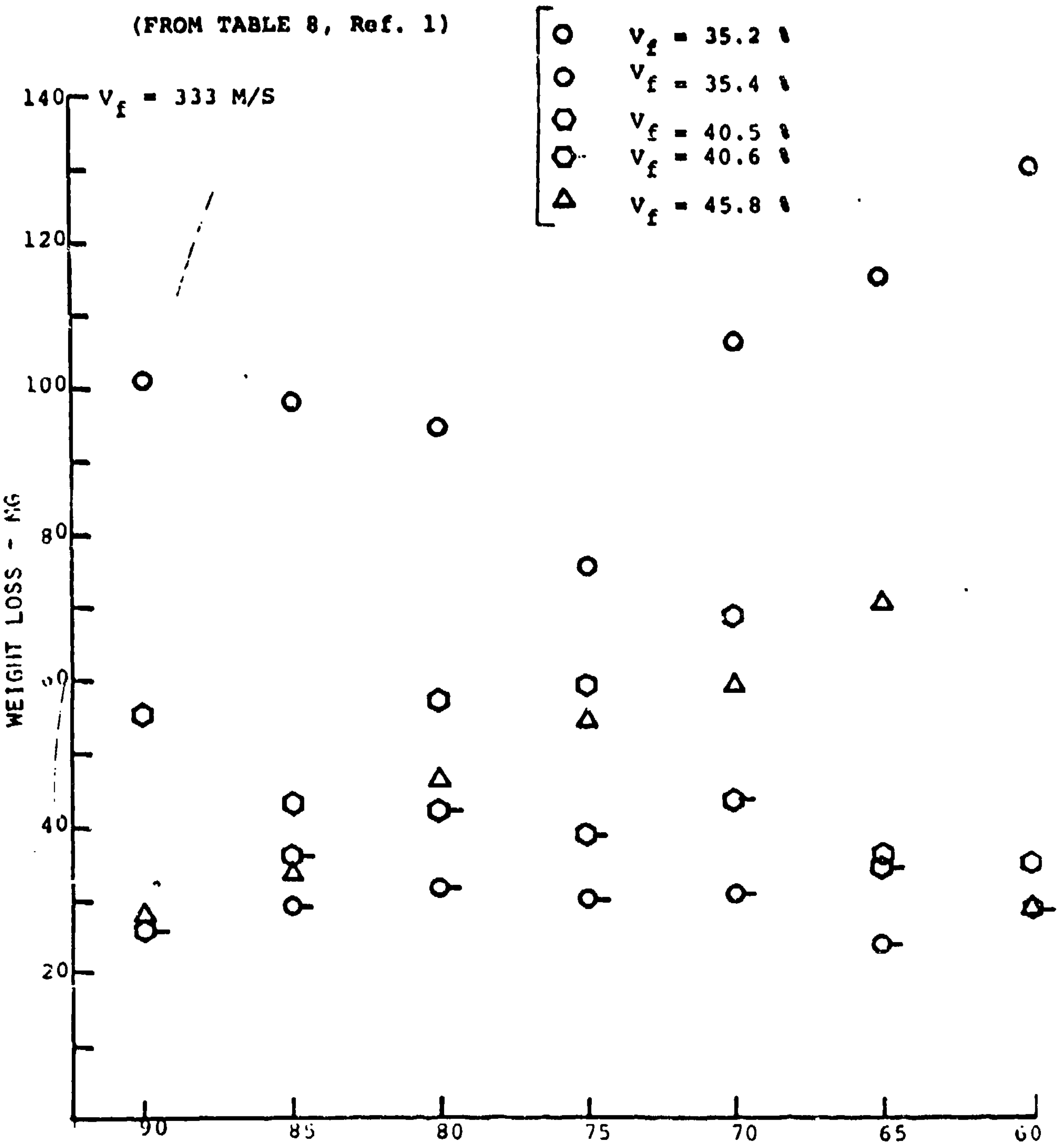


FIGURE 4 EFFECT OF FIBER AND IMPACT ANGLE ON EROSION OF EPON 828/MPDA - NOMEX

(FROM TABLE 8, Ref. 1)



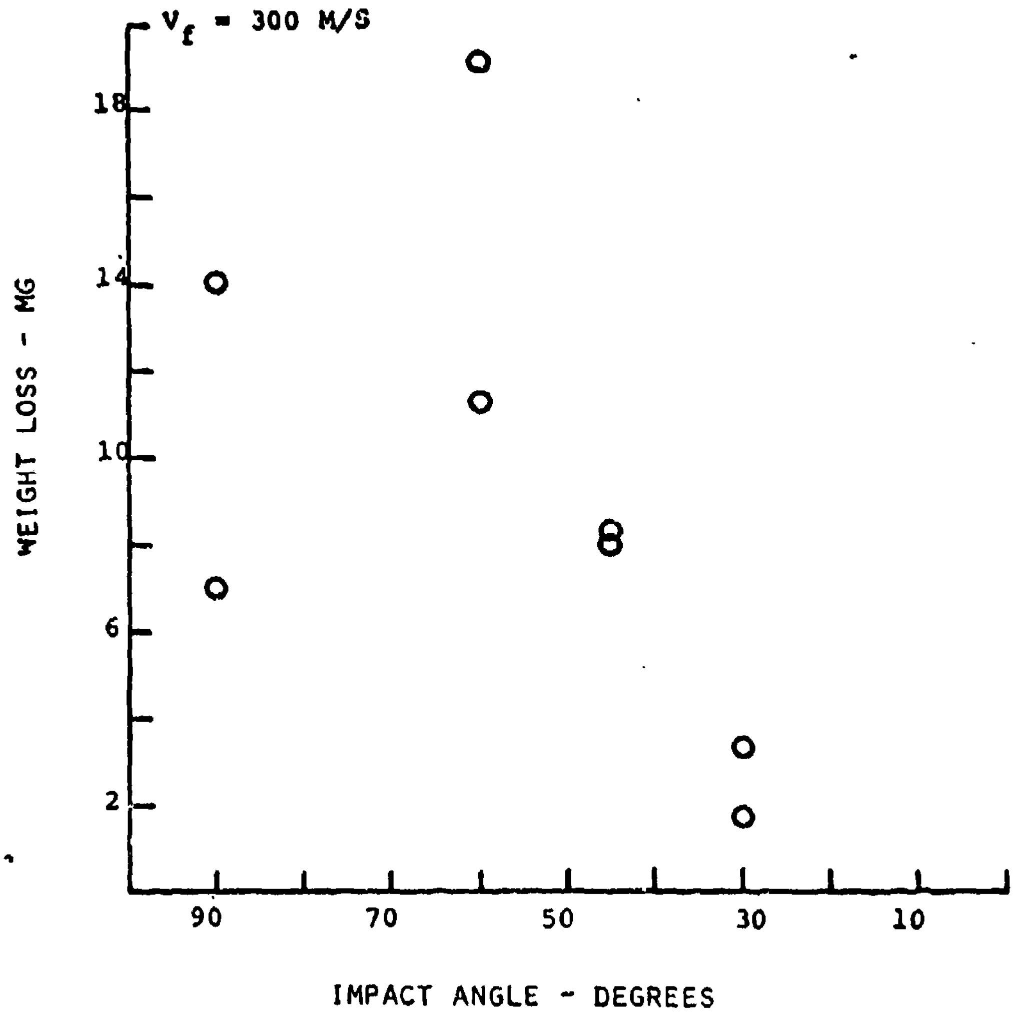
FIBER AND IMPACT ANGLE - DEGREES

* RAINDROP VELOCITY VECTOR PARALLEL TO FIBERS

NOTE: DATA NORMALIZED LINEARLY TO WEIGHT LOSS AT 30 SEC EXPOSURE

FIGURE 5 EFFECT OF IMPACT ANGLE ON EROSION OF EPON 828/MPDA - EGG GLASS (FIBERS @ 90° TO SPECIMEN SURFACE)

(FROM TABLE 7 REF. 1)



NOTE: DATA NORMALIZED LINEARLY TO WEIGHT LOSS @ 30 SEC EXPOSURE

FIGURE 6 WEIGHT LOSS FOR FIBERS NORMAL TO SURFACE AND RAINDROP VELOCITY VECTOR AT AN ANGLE TO SURFACE

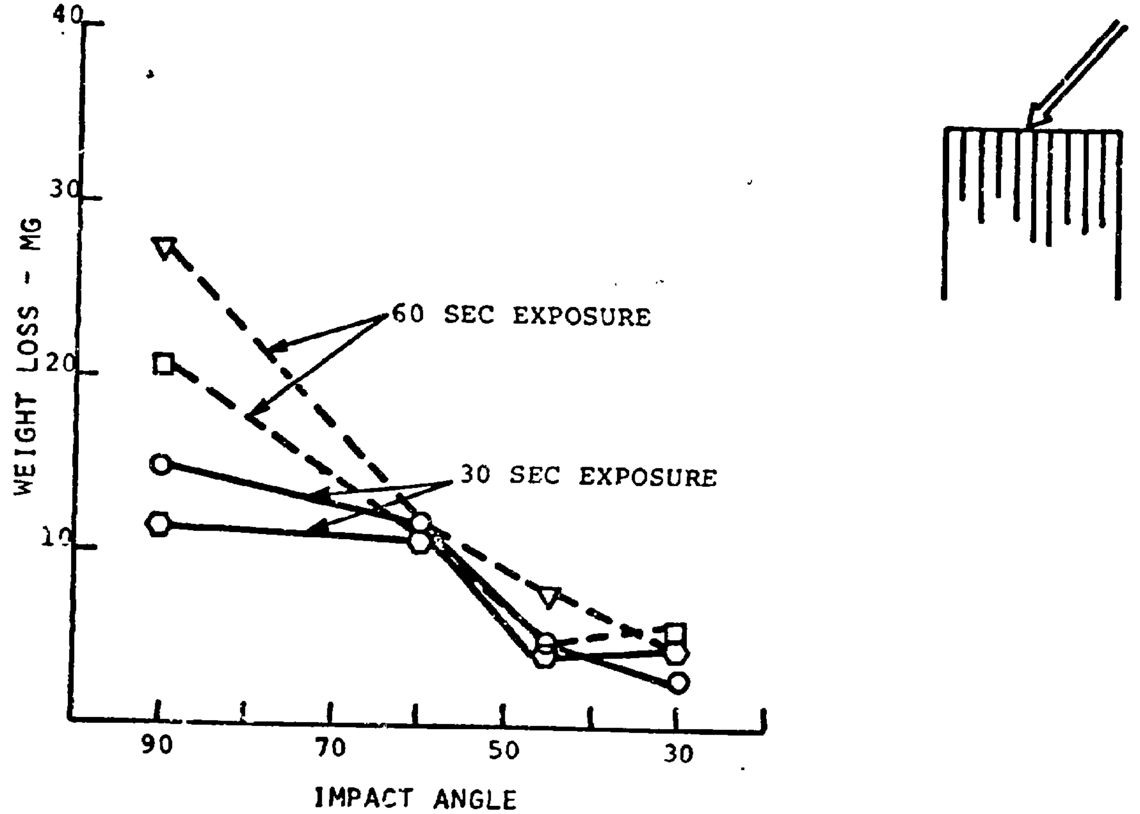


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FIGURE 7 WEIGHT LOSS FOR NORMAL IMPACT AND FIBERS AT AN ANGLE TO SPECIMEN SURFACE

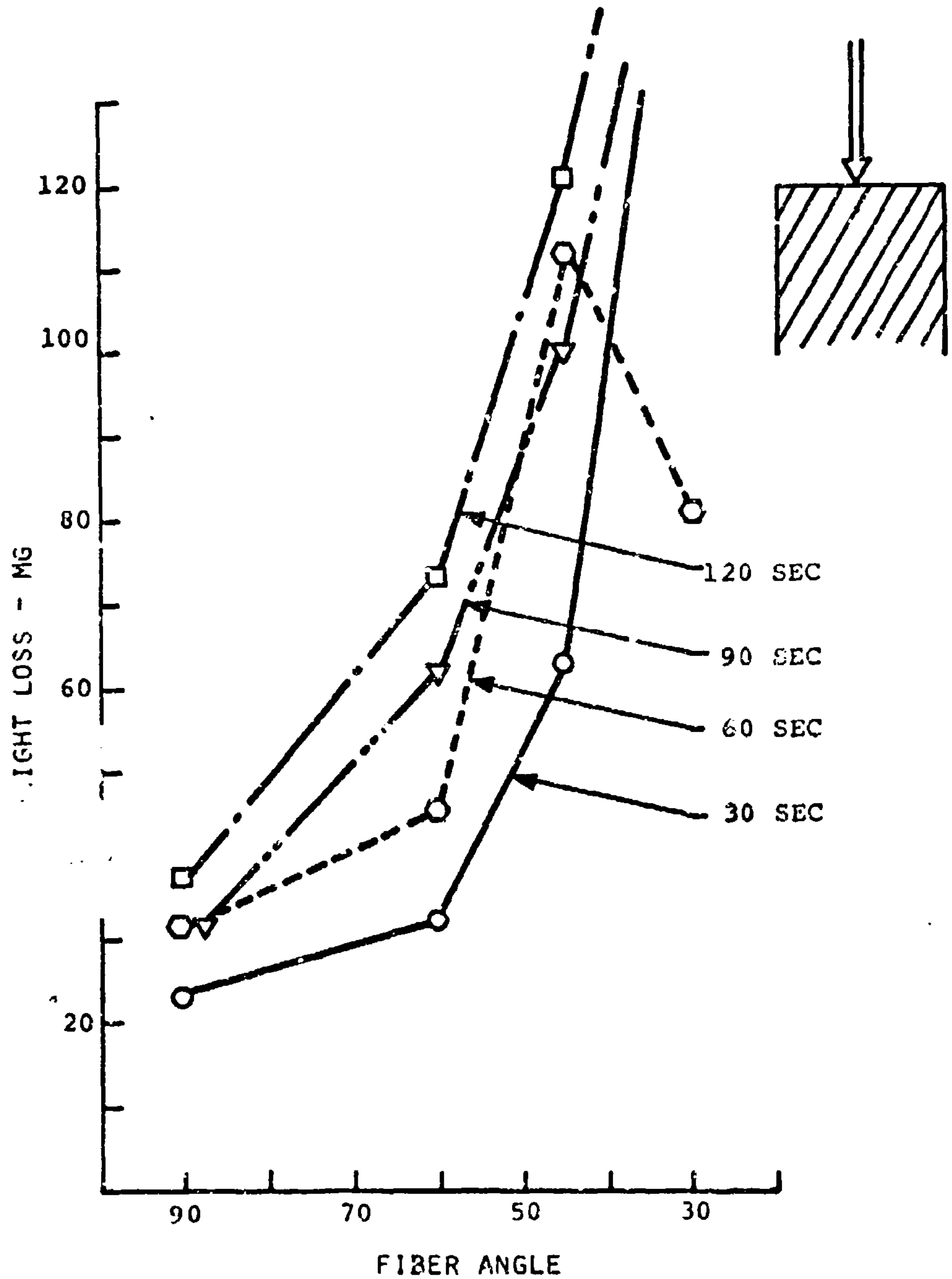


FIGURE 8 WEIGHT LOSS FOR FIBER ANGLE EQUAL TO IMPACT ANGLE

I.E. RAINDROP VEL. VECTOR PARALLEL TO FIBER

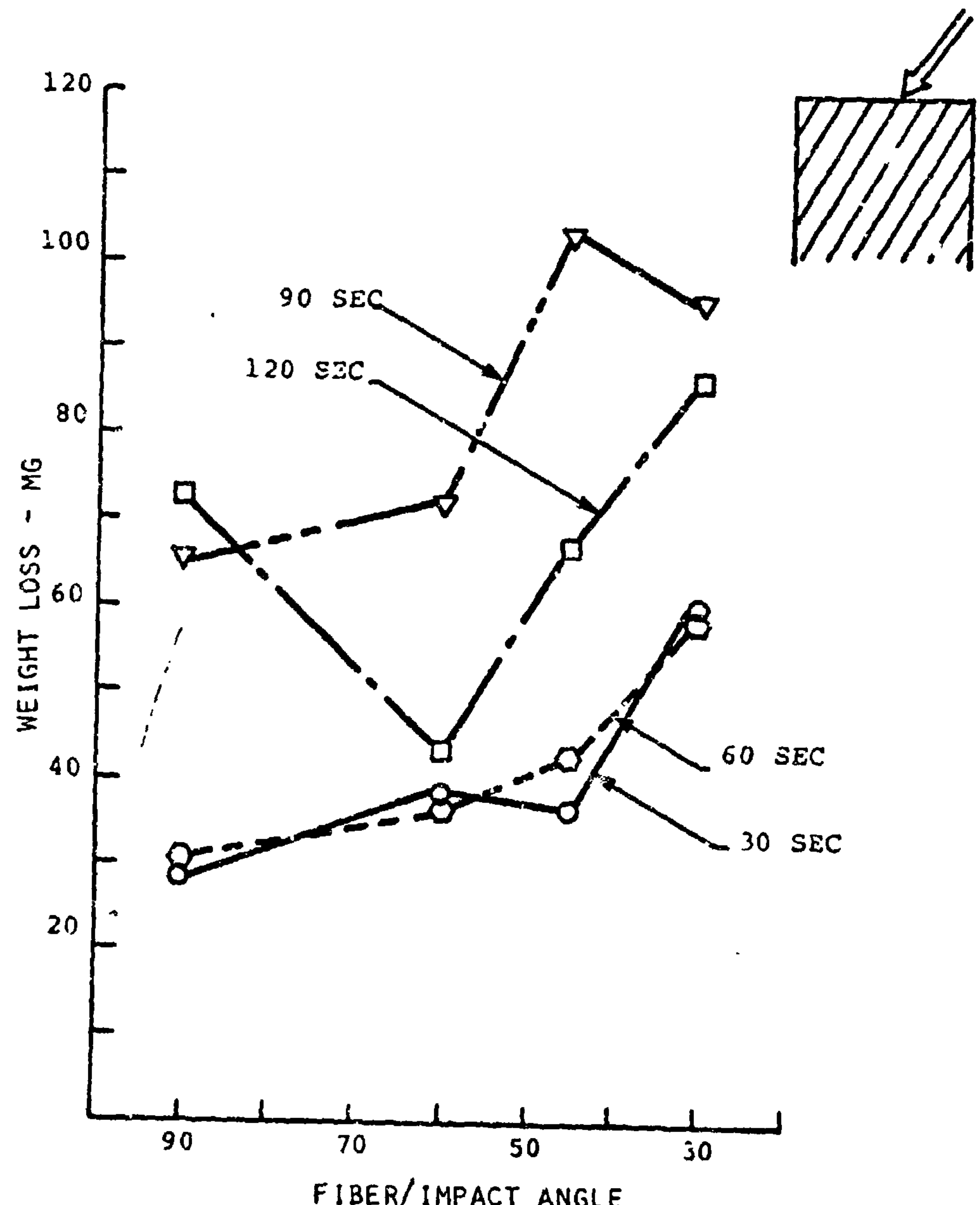


FIGURE 9 4-D NOMEX WEAVE - EPON 828/MPDA - MATRIX
IN PLANE MODULUS

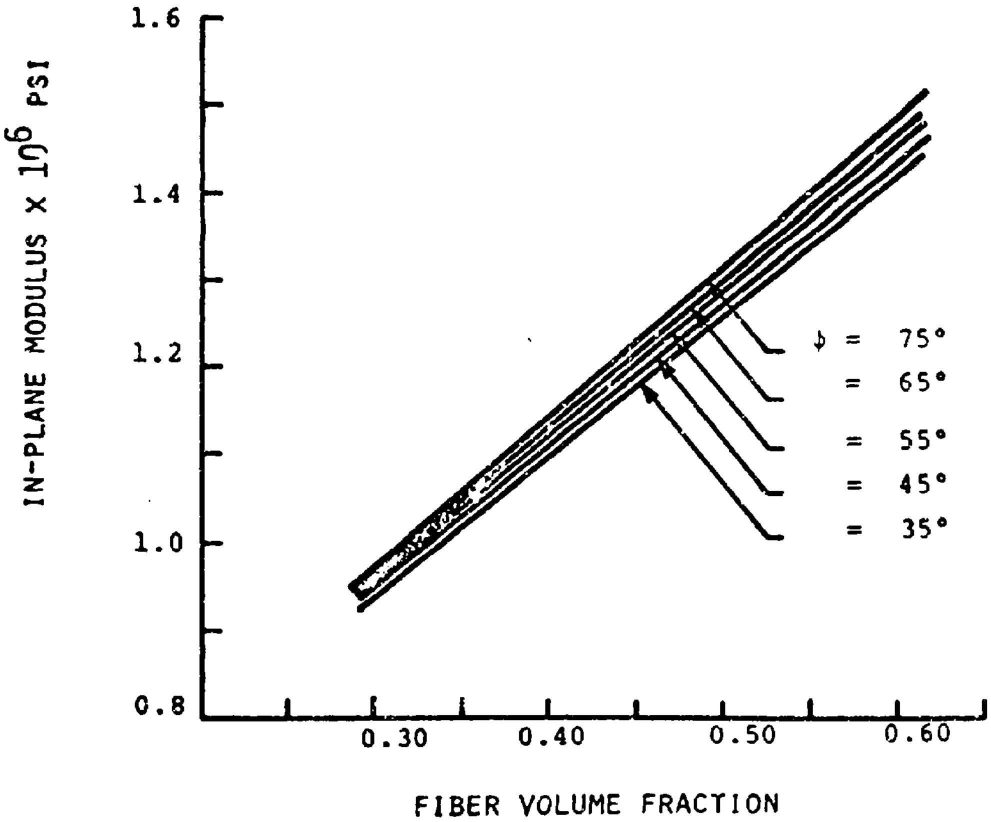


FIGURE [illegible] - 3-D ORTHOGONAL - V_F TOTAL = 60% - EPON 828/MPDA MATRIX

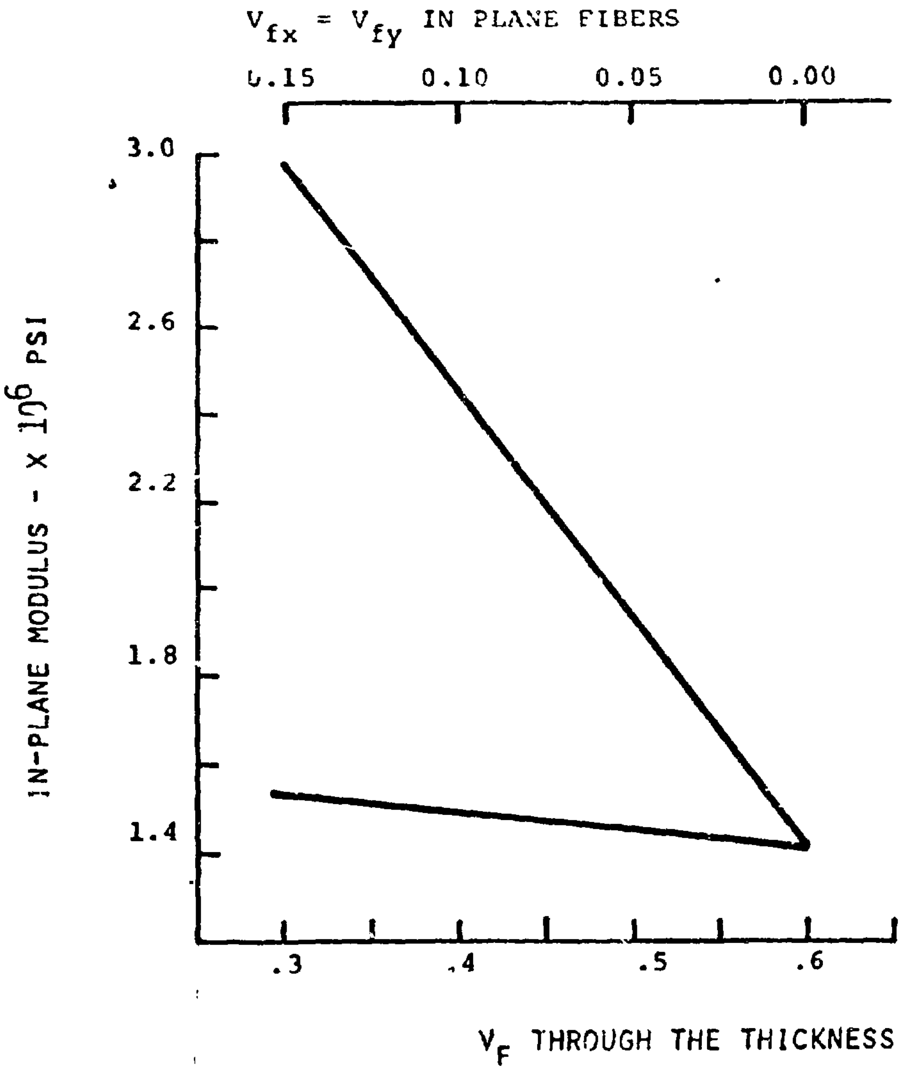


FIGURE 11

ELASTIC MODULI FOR ANGLE INTERLOCK MATERIAL

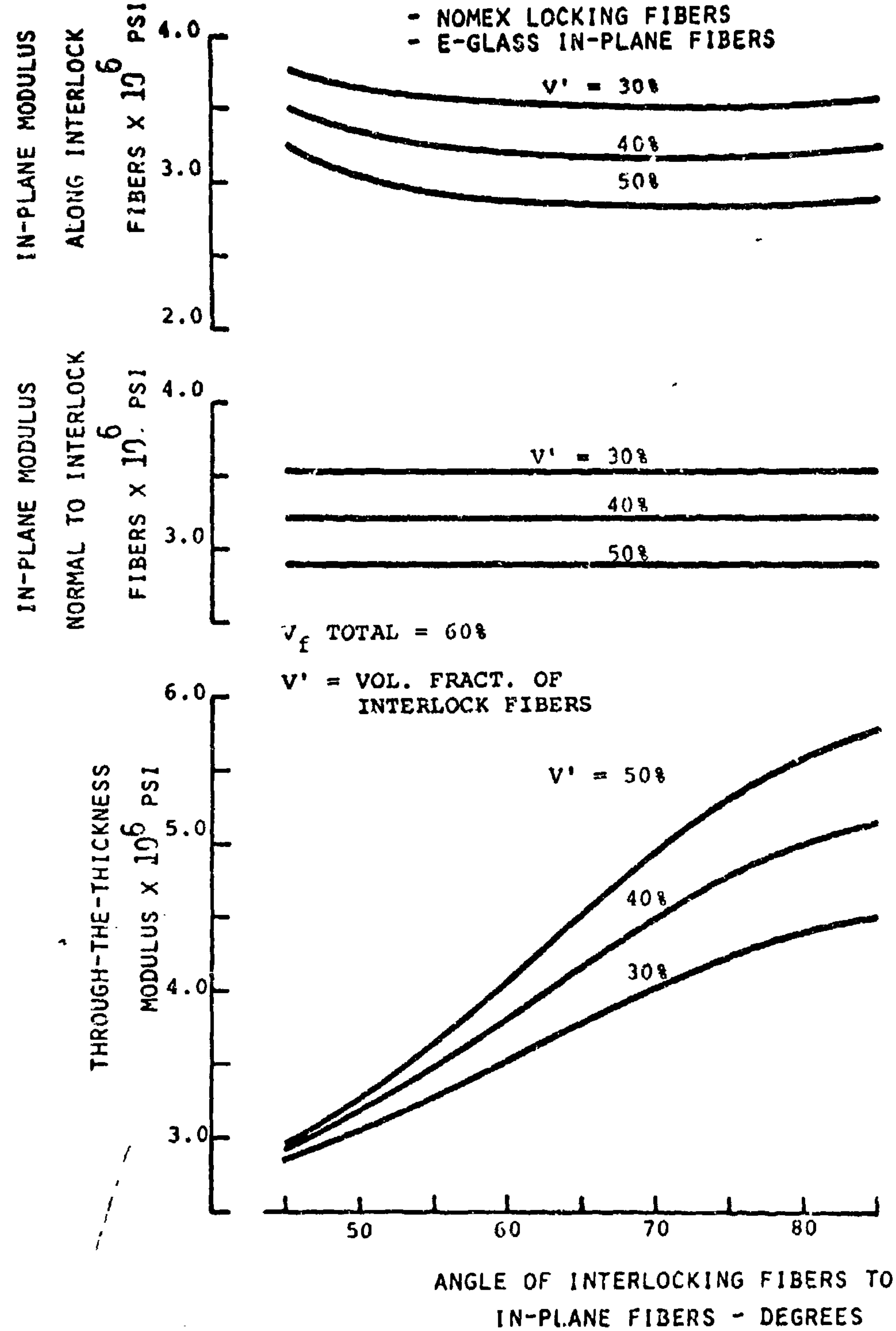


FIGURE 12 ELASTIC MODULI FOR ANGLE INTERLOCK MATERIAL - KEVLAR 49 FIBERS

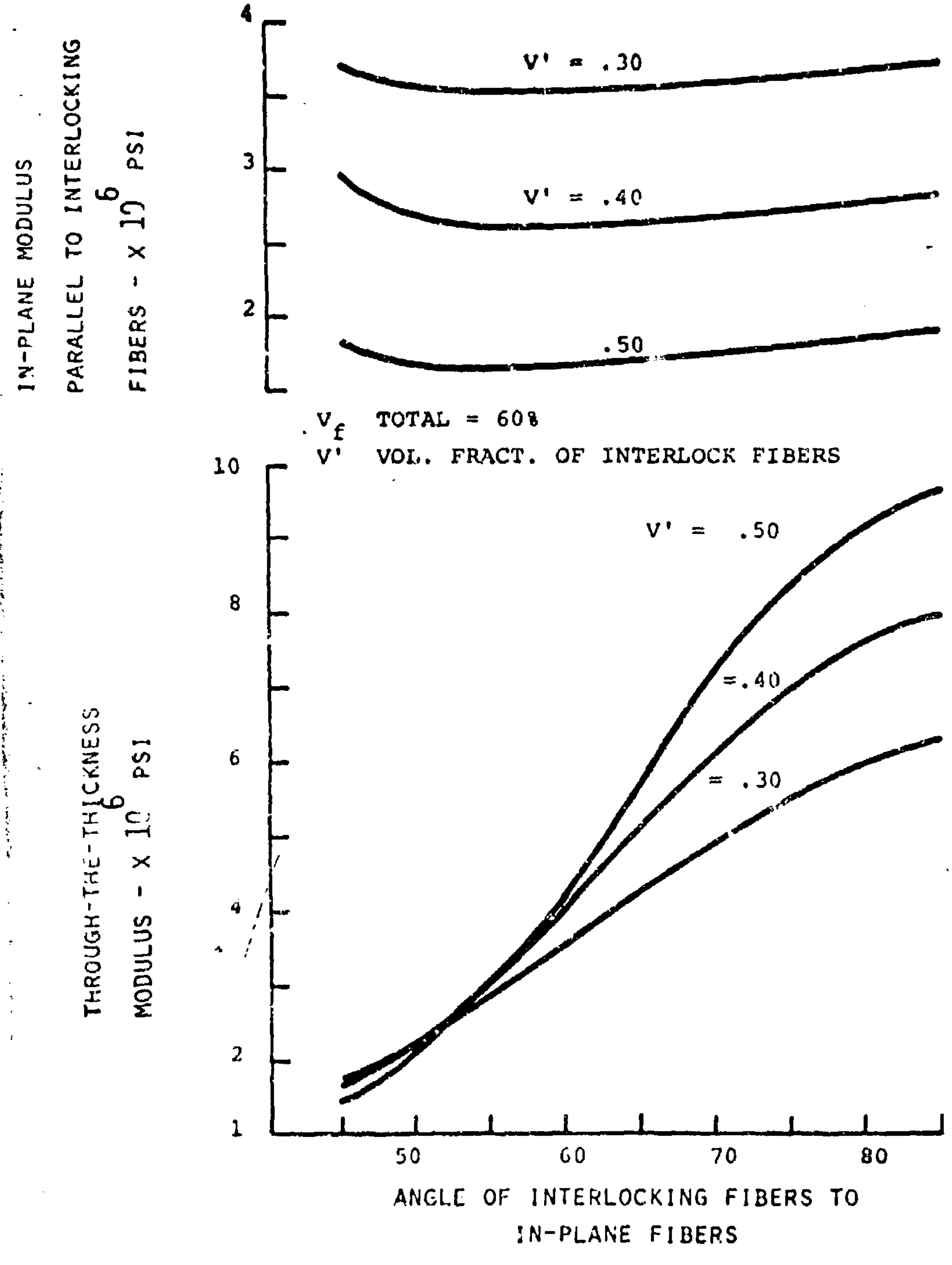


FIGURE 13 IN-PLANE TENSILE STRENGTH
-4D NOMEX
(BUNDLE SHEAR STRENGTH = 5000 PSI)

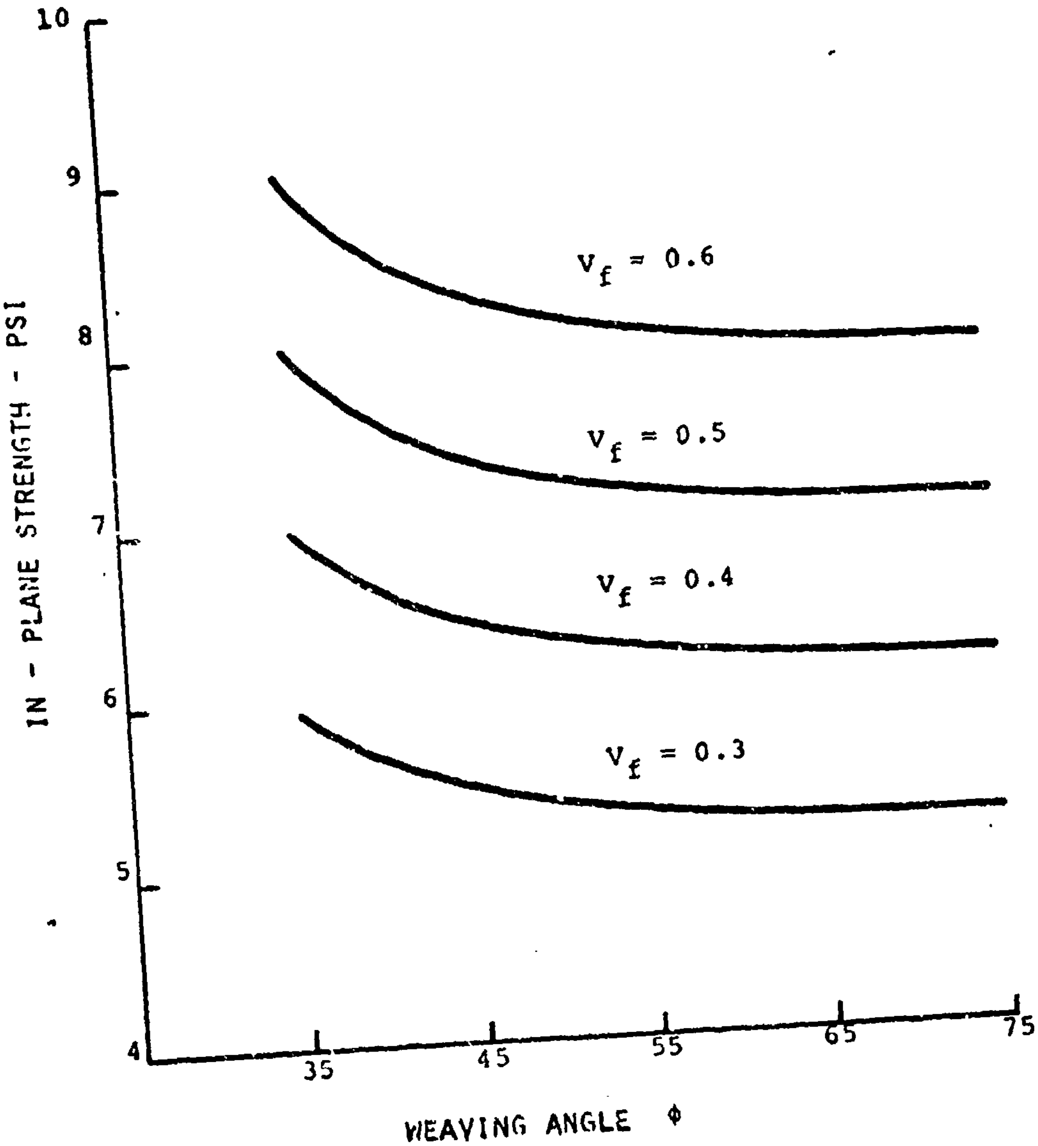


FIGURE 14 IN-PLANE STRENGTH OF ALL NOMEX 3-D WEAVE VS ANGLE OF IN-PLANE FIBERS TO PLANE

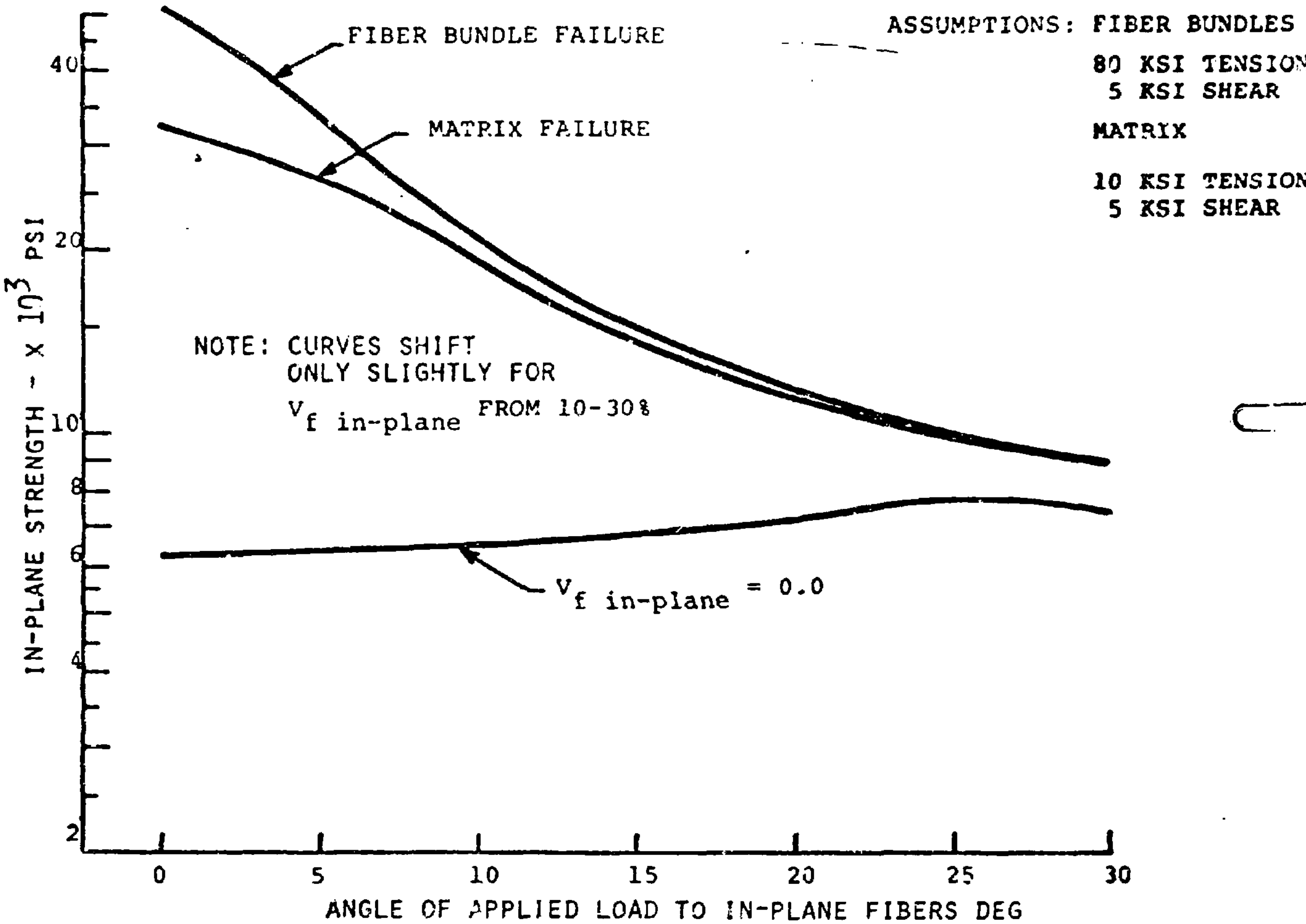


FIGURE 15 IN-PLANE STRENGTH OF 3-D WEAVE MATERIAL
(NOMEX THROUGH THE THICKNESS & E-GLASS IN-PLANE)

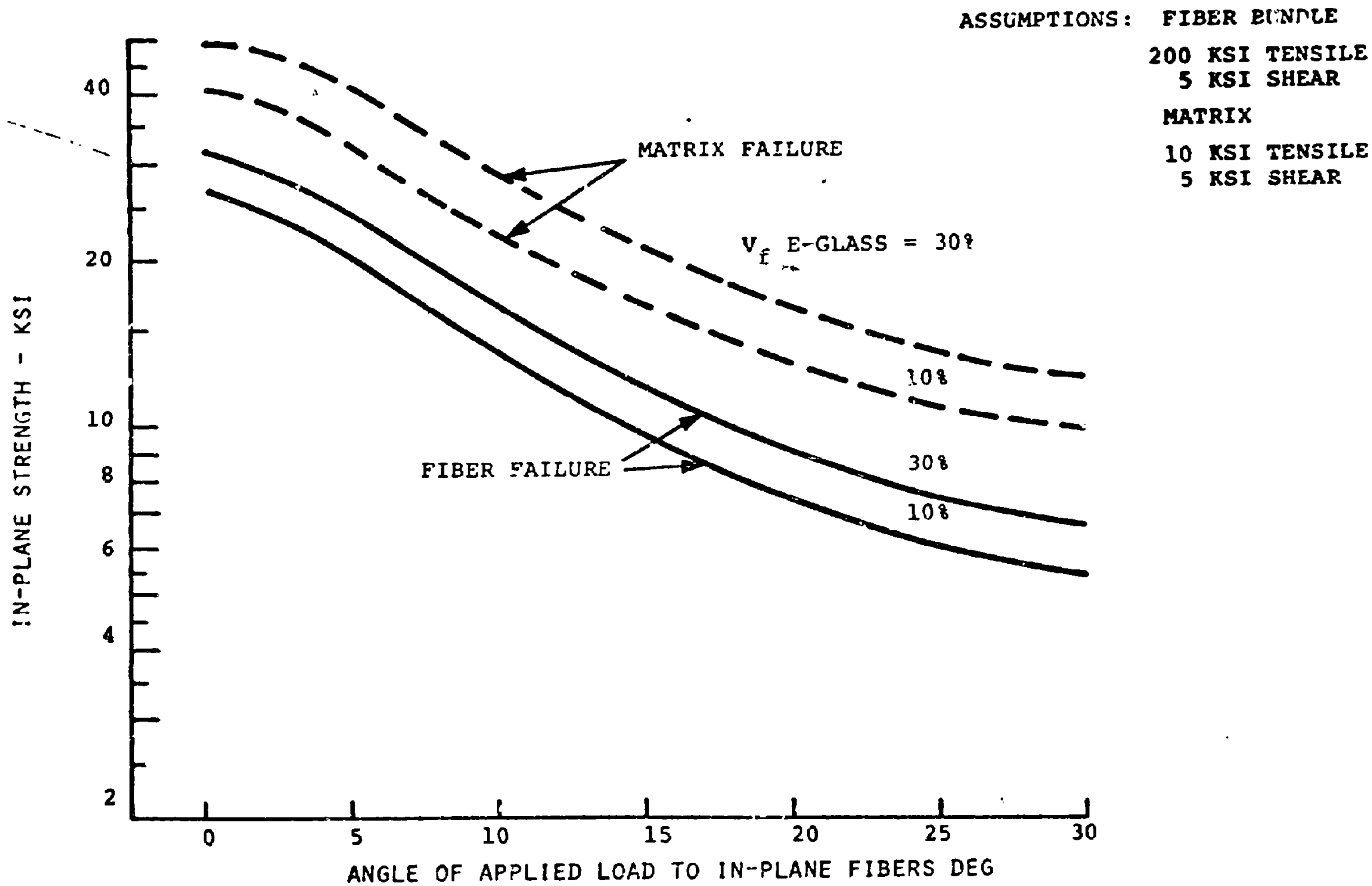


FIGURE 16 IN-PLAN STRENGTH OF 4D - NOMEX WEAVE, $V_{F\ TOTAL} = 0.60$

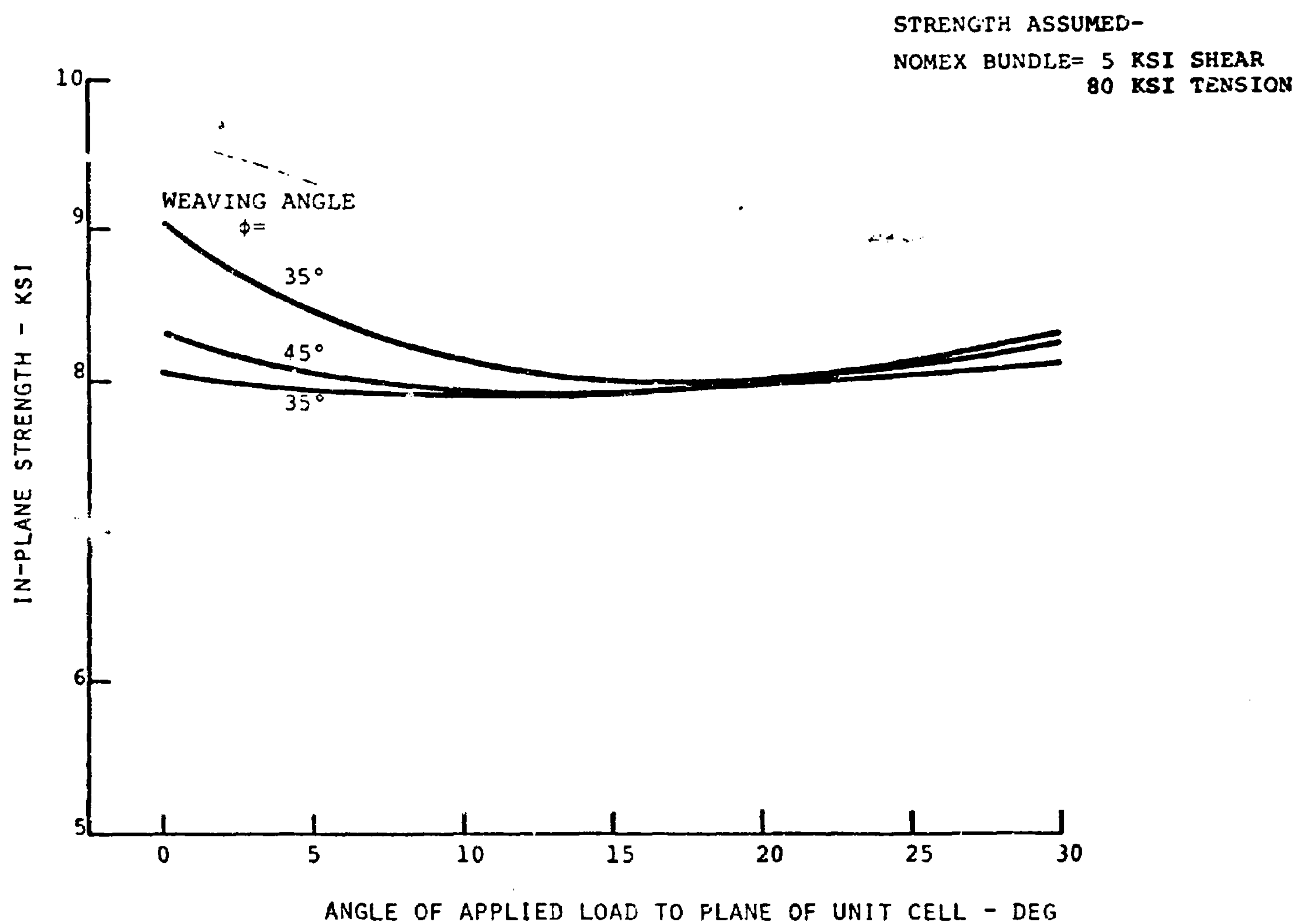


FIGURE 17 RATIO OF IN-PLANE STRENGTH TO FIBER BUNDLE STRENGTH FOR ANGLE INTERLOCK MATERIAL NOMEX INTERLOCKING FIBERS E-GLASS IN-PLANE FIBERS

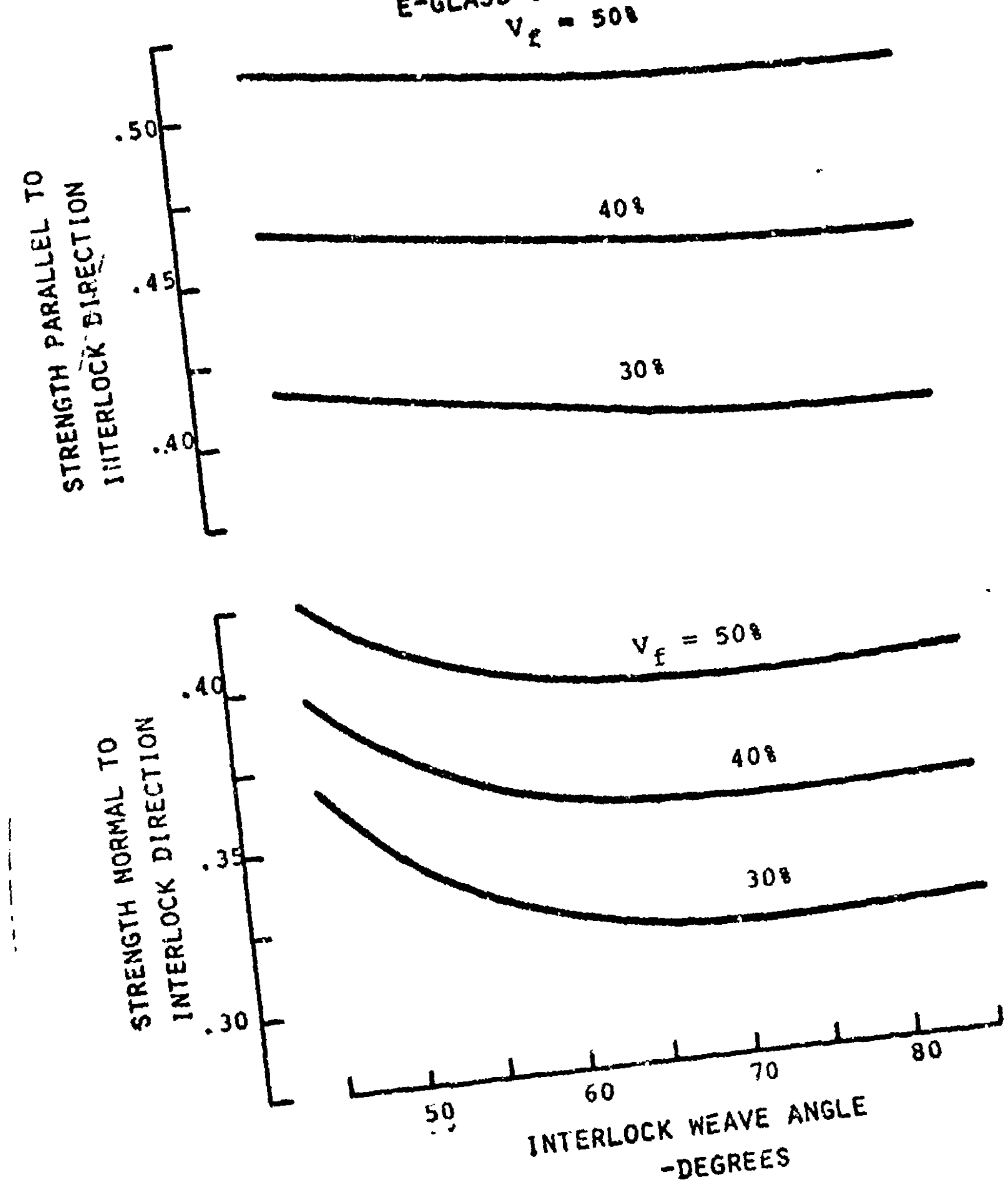


FIGURE 18 A TYPICAL 3-D ORTHOGONAL UNIT CELL

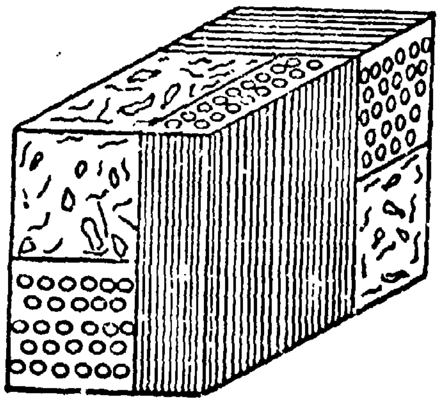
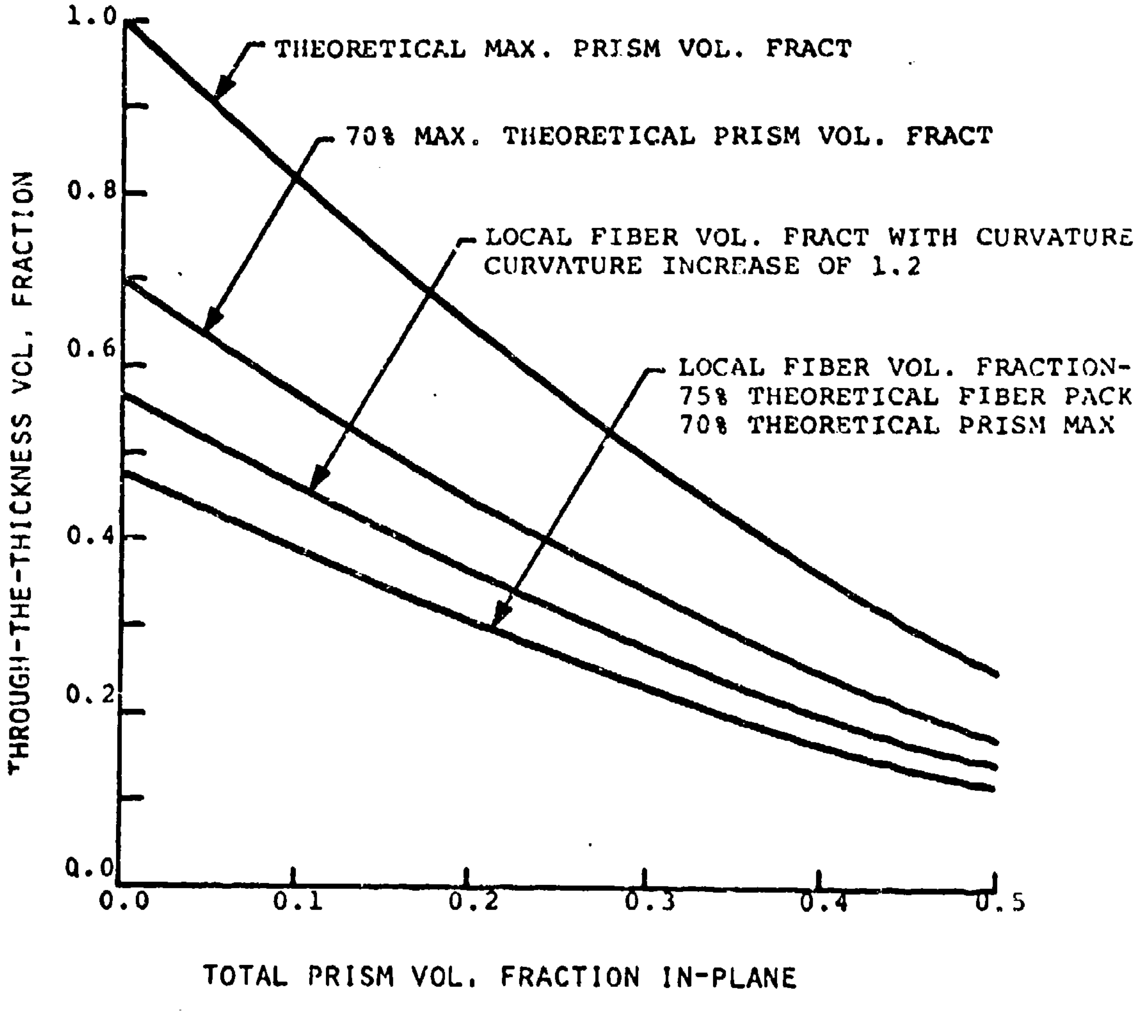


FIGURE 19 3-D ORTHOGONAL UNIT CELL VOLUME FRACTIONS



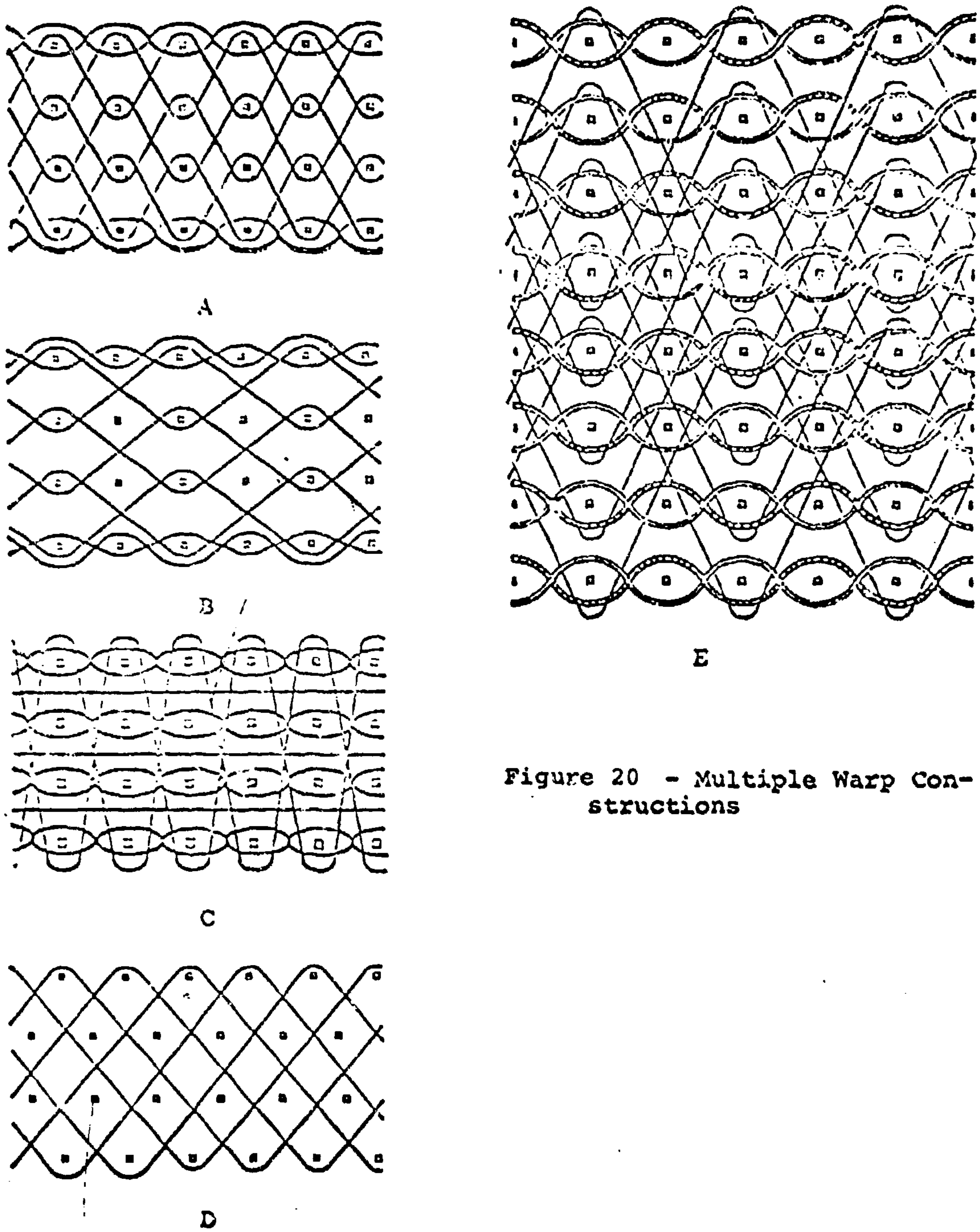
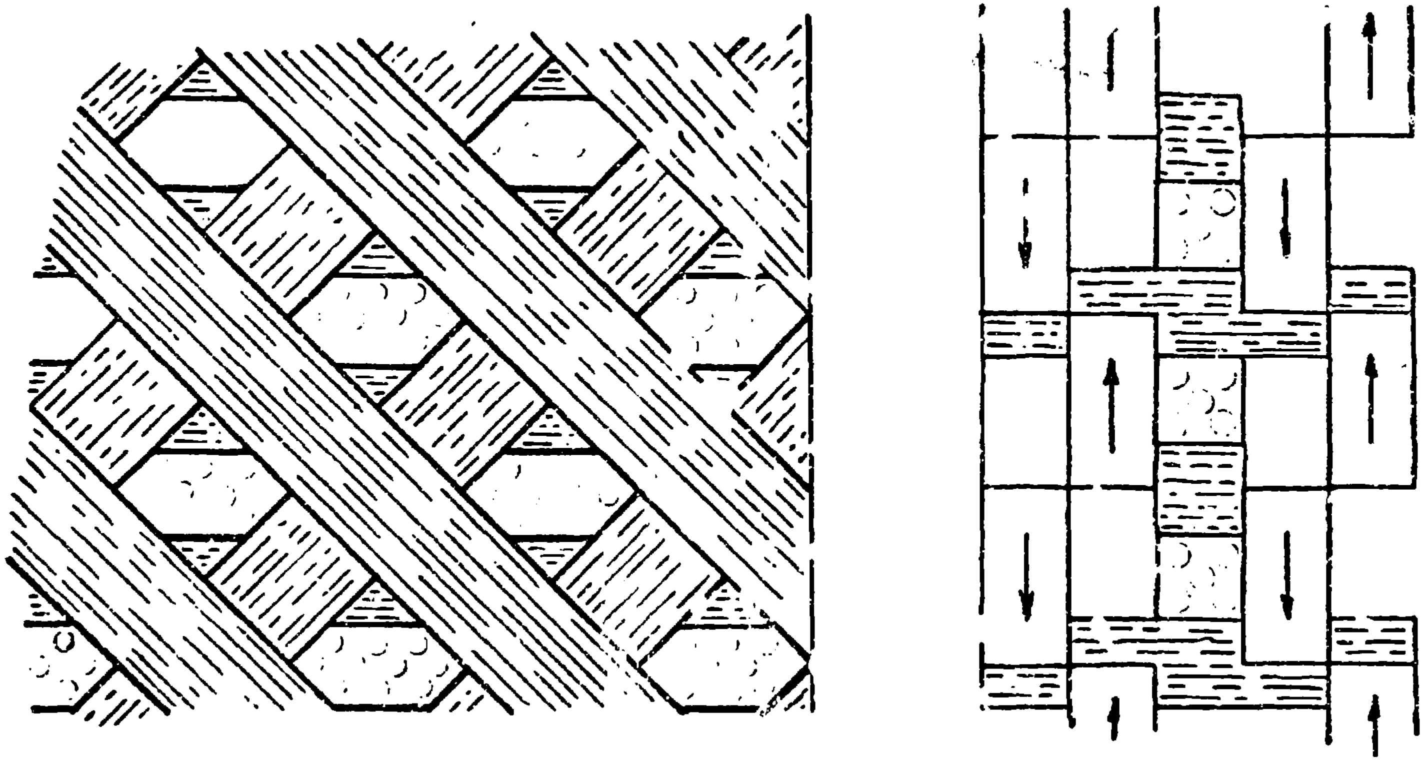


Figure 20 - Multiple Warp Constructions

FIGURE 21 ANGLE INTERLOC UNIT CELLS



SIDE VIEW   FRONT VIEW

FIGURE 22 UNIT CELL PRISM VOLUME FRACTIONS VOL. FRACTION OF THROUGH THE THICKNESS FIBERS AND ANGLE INTERLOCK FIBERS FOR VARIOUS IN-PLANE VOL. FRACTIONS

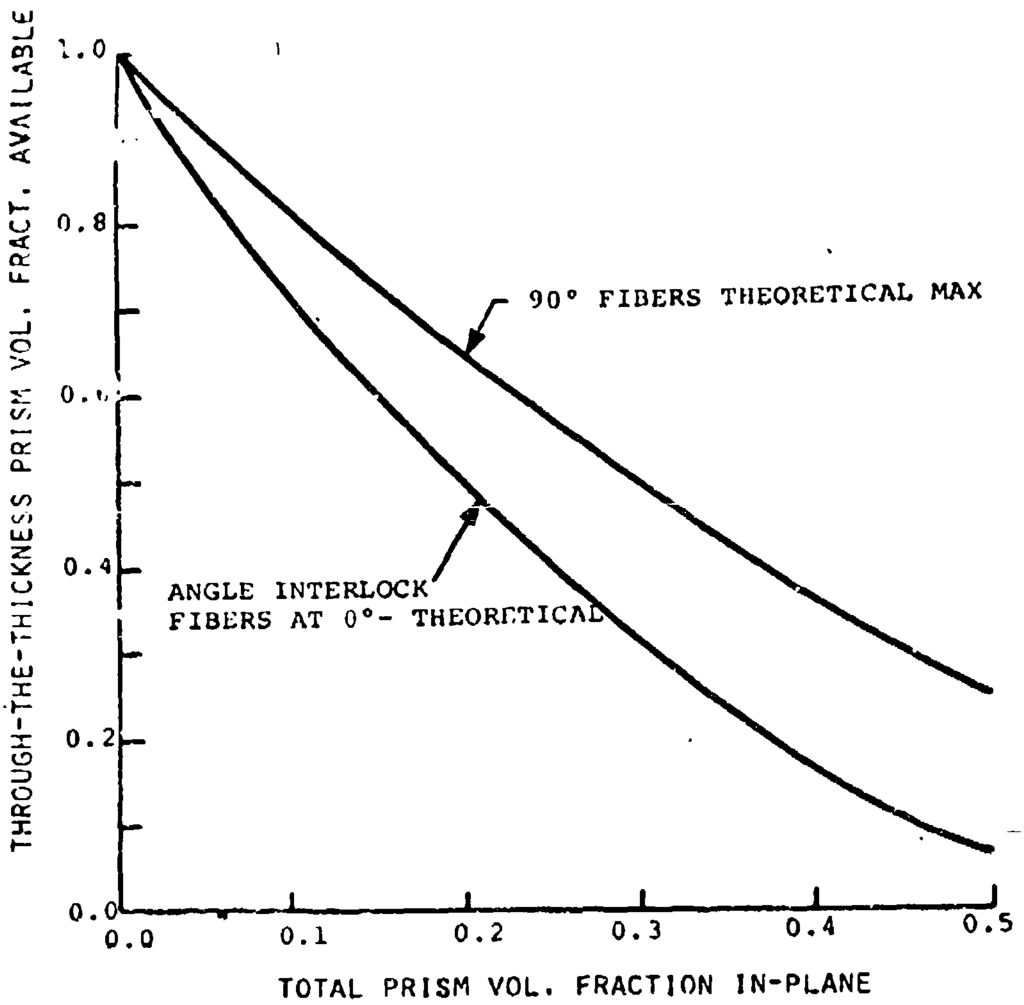
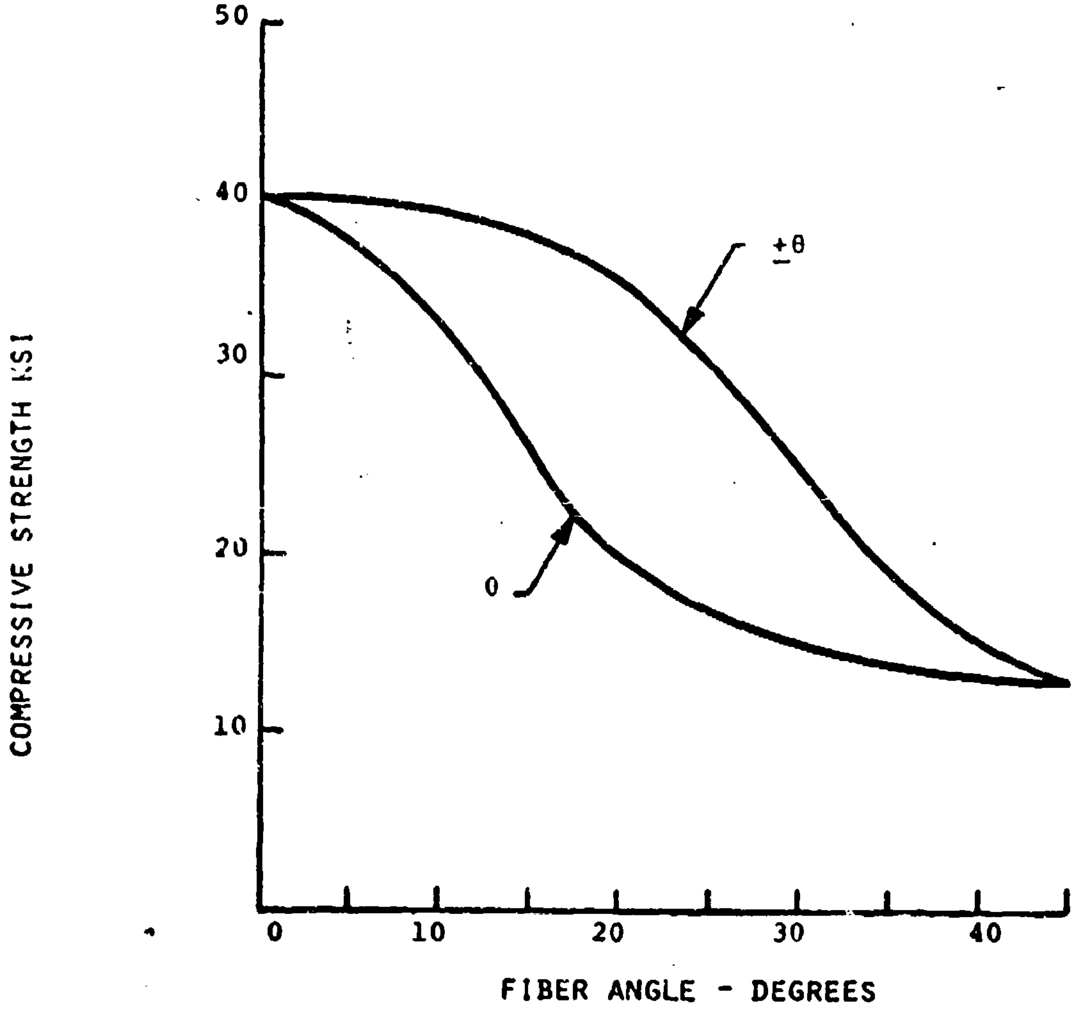


FIGURE 23 COMPRESSIVE STRENGTH OF 1-D AND A $\pm\theta$ LAMINATE OF KEVLAR 49/EPOXY



APPENDIX A
X-D PROPERTIES VIA MSC'S X-CAP PROGRAM

The MSC X-CAP (X-Directional Composite Analysis Program) has been developed for the analysis of composite unit cells. The unit cell is modeled as a rectangular parallelopiped composed of fiber bundles oriented in various directions (the three edge, four body diagonal, and/or six face diagonal directions) and having a matrix material in the interstices between fiber bundles. The amount, or existance, of fiber bundles in any given direction is controlled by specifying the fiber bundle volume fraction in each direction. Each of the edge fiber materials can be specified as different material, and the diagonal fiber materials is specified, thus allowing treatment of hybrid, composites. The constituent materials may have transversely isotropic elastic constants as well as thermal expansion coefficients.

Material porosity and configurations of material at less than maximum theoretical density can be treated. The matrix material is assumed to behave like a material with dispersed voids throughout. Reduced effective elastic constants are computed for the given porosity, and the effective constants are utilized in the program. The program has the flexibility to treat different matrix properties in the fiber bundle and interstitial matrix regions, thus the effects of different void contents in the fiber bundle and interstitial regions may be treated.

Solution for unit cell elastic properties is accomplished in the following manner: Properties are first computed for unidirectional (1-D) impregnated fiber bundles using the theoretical developments in reference 5. The 1-D fiber bundles are assembled to form a unit cell, with given fiber bundle orientation and volume fraction information, along with interstitial matrix description. Then the unit cell mechanical properties are computed. The governing equations employed for elastic constants were developed in reference 6.

APPENDIX B

OFF-AXIS LOAD CAPABILITY OF 3-D, 4-D, and 5-D WEAVES

The often stated attractivness of multi-directional composites is the ability of these materials to handle loading in directions other than in the fiber direction and in shear. To examine the statements a little more closely and to determine the amount of improvement which might be obtained with a 4-D or 5-D composite over the more conventional 3-D composite, an analysis of these materials was made in a separate program, Ref. 4, and the results are directly applicable.

For all three materials it was assumed that the total fiber volume fraction was 50 percent, with fiber and matrix properties being the same in all cases. The 3-D material was assumed to be balanced in that one-third of the total number of fibers were placed in each of the three fiber directions. The 4-D material was also assumed balanced to be in a 1 x 1 x 1 weave yielding a projected fiber angle of 45 degrees. For the 5-D material, one-fifth of the fibers were placed in each of the five fiber directions, resulting in 80 percent of the fibers being in diagonal directions and 20 percent being in one of the three edge directions. The 5-D material was additionally assumed to have a 1 x 1 x 1 configuration, which resulted in projected fiber angles of 45 degrees.

The results are summarized in table B-1. The fiber strengths were assumed to be 100 ksi in tension and 4.5 ksi in shear. In all cases, fiber shear strength governed failure, thus the choice of fiber shear strength would modify all results in Table 2 proportionally. The inherent axial strength of the 3-D materials is apparent in Table B-1.

Note that for face diagonal loading and body diagonal loading relative to the unit cell, the 3-D strength drops to 30 and 37 percent of the axial strength, respectively.

This clearly illustrates a very significant strength reduction for off axis loading of 3-D. For 4-D material the axial load case is the weakest loading direction with face diagonal and body diagonal (loading along one fiber) resulting in 34 and 132 percent increases in strength over the axial strength. The 5-D shows an increase in strength of 41 and 100 percent of the axial load capability for face diagonal and body diagonal loading, respectively, and a 65 percent increase in strength for transverse loading in the fifth fiber direciton (see Table B-1).

The obvious conclusion from the tensile load cases is that there is considerable strength variation in all cases with the least variation occurring in 5-D and the most in 3-D material. Note, however, that when the axial strength of 4-D material is sufficient for a given application, the off-axis strength will be greater. A 3-D component which may be adequate for axial loads, on the other hand, may be design critical for any off-axis loading.

Consider next the strengths due to applied shear stresses indicated by the analyses. The advantage of 4-D material over 3-D is obvious when one considers that the 4-D material will exhibit roughly four times the strength in shear of corresponding 3-D material. The shear strength of 4-D material is in fact roughly equal to the tensile strength.

From the previous results it is obvious that one must consider the stress state which will be applied to a material before passing judgement on the fiber configuration most suitable. Naturally cost must also be considered since 4-D weaves will generally cost more than 3-D weaves to fabricate.

TABLE B-1 Comparison of 3-D, 4-D, and 5-D Silica/Silicone Material under various loading conditions

Strength Assumptions: Fiber UTS=100 kis
Fiber Shear Strength = 4.5 ksi

Material Loading	3-D	4-D	5-D
Axial Tension	20,880	7,715	7,500
Face Diag. Load	6,080	10,350	10,635
Body Diag. Load	7,715	17,940	15,050
Face Shear	3,040	11,960	8,440
Diag. Shear	3,635	16,915	9,830

Note: For transverse loading the 3-D and 4-D strengths are the same as for axial loading, but for 5-D loaded in the direction of the fifth fiber, results show a 65 percent increase in strength to 12,480 psi.